ENERGY ECONOMY AND ENVIRONMENT INTEGRATED LARGE SCALE MODELING AND ANALYSIS OF THE TURKISH ENERGY SYSTEM

by
Mine Işık
B.S., Industrial Engineering, Dogus University, 2008
M.S., Industrial Engineering, Istanbul Technical University, 2010

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ABSTRACT

ENERGY ECONOMY AND ENVIRONMENT INTEGRATED LARGE SCALE MODELING AND ANALYSIS OF THE TURKISH ENERGY SYSTEM

Need for energy is constantly increasing as globalization spreads, and is becoming a very important input for economic development. As energy resources are scarce, safe and sustainable supply of energy, efficient use, reduction of greenhouse gasses and environmental protection, price changes and instabilities in fuel prices, transformation from usage of fossil fuels to usage of renewable energy sources, etc. have become strategically important for countries. Upon realizing the severity of this situation, nations try to conduct policies concerning accurate management of energy. In this context, decisions on energy generation, transmission and consumption are of primary importance. For this very reason, policy makers are in urgent need of an appropriate modeling methodology that provides accurate projections on future forecasts. The purpose of this thesis study is to propose a model that has a bottom-up structure with large-scale energy-economy-environment modeling framework focusing on the mechanisms and relationships that represent Turkish energy sector realistically. In this regard, Boğaziçi University Energy Modeling System (BUEMS) model is established and validated by comparing the results of scenarios with The Integrated MARKAL-EFOM System (TIMES) modeling framework in accordance with the Turkish national energy sector data. The primary objective is obtaining meaningful and trustworthy results by modeling the energy sector with the highest factualness. An extensive range of emission mitigation scenario analysis is evaluated to provide feedback of testing energy policy choices (emission tax, emission bound, investment on fuel supply infrastructure) and analytical insights on the system behavior of Turkish energy system for the period out to 2052.

ÖZET

TÜRK ENERJİ SİSTEMİNİN ENTEGRE GENİŞ ÖLÇEKLİ ENERJİ-EKONOMİ-ÇEVRE MODELİ VE ANALİZİ

Küreselleşmenin de yaygınlaşmasıyla birlikte enerjiye duyulan ihtiyaç her geçen gün artmakta ve ekonomik kalkınma için önemli girdilerden biri haline gelmektedir. Enerji kaynaklarının kısıtlı olması nedeniyle, enerjinin güvenli ve sürdürülebilir temini, verimli kullanımı, sera gazı etkilerinin azaltılması ve çevrenin korunması, yakıt fiyatlarındaki değişim ve kararsızlıklar, fosil kaynaklardan yeni ve yenilenebilir enerji kaynaklarına doğru geçiş vb. konular tüm ülkelerin politikalarında yer alması gereken, stratejik önem arz eden konulardır. Bu durumun ciddiyetininin anlaşılması ile, ülkeler karbon emisyonu sorunuyla ilgili politikalar oluşturmaya çalışmaktadırlar. Bu bağlamda, enerji üretimi, iletimi ve tüketim kararları birincil önem taşımaktadır. Bu amaçla, politika kurucular enerji tahminleri üzerine tutarlı izdüşümleri sağlayan modelleme metodolojilerine oldukça ihtiyaç duymaktadırlar. Bu tezin amacı “Bottom-up” yapıda kurulmuş, geniş ölçekli enerji-ekonomi-çevre modelleme sistemine sahip Türkiye enerji sektörünü gerçekçi bir şekilde temsil edecek mekanizma ve ilişkileri içeren bir model önermektir. Bu bağlamda, Boğaziçi Üniversitesi Enerji Modellemesi Sistemi (BUEMS) modeli kurulmuş ve Türk ulusal enerji sektörü verilerine göre Entegre MARKAL-EFOM Sistemi (TIMES) modelleme sistemi ile elde edilen senaryolar ile elde edilen sonuçlar doğrulanmıştır. Temel amaç, enerji sektörünü modelleyerek gerçekçi, anlamlı ve güvenilir sonuçlar elde etmektir. 2052 yılında kadar emisyon azaltımını sağlayacak alternatif politika opsiyonları (emisyon vergisi, emisyon üst sınırı, yakıt tedariği sağlayacak altyapı yatırımları) altında Türk enerji sisteminin nasıl davrandığını gösteren analitik sonuçlar sağlayacak, geniş ölçekte senaryo analizleri gerçekleştirilmiştir.

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act	Activity level
actflo	Activity conversion factor
addcost	Total annual additional costs
a	Annual availability factor
anncost	Total annual cost
baseload	Highest baseload power plants
bnd_fx	Fixed bound on a technology
bnd_lb	Lower bound on a technology
bnd_up	Upper bound on a technology
c	Energy Conversion Technology
cap	Capacity level
capt	Total capacity
capunit	Conversion factor between units of capacity and activity
cbnd(p)	Cumulative bound on a technology
celc	Electricity generation technology
cf	Capacity utilization factor
cg1	Input commodity group
cg2	Output commodity group
com_ie	Infrastructure efficiency
cp	Process Technology
crf	Capital recovery factor
d	Demand technology
dagr	Agriculture sector demand technology
decomcost	Decommissioning cost
delivent	Unit delivery cost
dind	Industry Sector Demand Technology
discount	Discount rate
dmd	Demand service
drsd	Residential and Commercial Sector Demand Technology
dtranom	Unit transmission cost

dtrn	Transport sector demand technology
e	Energy source
edistcost	Unit distribution and transmission cost of electricity
edistinv	Unit investment cost for electricity distribution system
eff	Efficiency rate
ems	Emission level
envcost	Total annual environmental costs
ereserv	Peaking reserve factor for electricity generation
etraninv	Unit investment cost for electricity transmission system
fixcost	Fixed annual costs
fixom	Fixed operating and maintenance cost
fixtaxsub	Fixed annual tax cost
flofunc	Efficiency ratio of technology that consumes multiple inputs
fr	Fraction of the year
impent	Energy carrier requirements
inpent	Level of input required per unit activity
inv	Investment level
incost	Total annual investment costs
l	Time segment
lbr	Annual decay rate
life	Lifetime
ncap_dcost	Decommissioning capital cost
ncap_pasti	New capacity of past investments
opercost	Total annual operational costs
outent	Level of output generation per unit activity
p	Any technology of the model
peakcon	Peaking contribution of capacity
reg_obj	Discounted objective value
resid	Residual capacity
rpc_ire	An import/export flow into/from of a commodity
salvage	Salvage value
salvcost	Unit salvage cost
sexp	Export technology

simp	Import Technology
sink	Quantity of commodity required per unit of new capacity
smin	Mining Technology
srnw	Renewable Technology
stg_eff	Efficiency of storage process
sup	Supply level
supcost	Total annual supply costs
t	Time period
tcost	Total system cost
teen	Transmission efficiency of electricity at period t.
tlife	Technical lifetime
ubr	Annual growth rate
ucf	Unit conversion factor
var_act	Annual activity level
var_blnd	Blending variable
var_cap	Current capacity level
var_comnet	Net amount of a commodity
var_comprd	Gross production of a commodity
var_elast	Variables used to discretize demand curves
var_flo	Flow of a commodity in or out of a process
var_ire	Flow of a commodity in or out of an exchange process
var_sin	Flow of a commodity in or out of a storage process
varcost	Variable annual cost
varom	Variable operating and maintenance cost per unit activity
y	Year
z	Emission type

LIST OF ACRONYMS/ABBREVIATIONS

AGE	Applied General Equilibrium Models
AGR	Agriculture Sector
ASP	Asphaltite
AIM	Asian-Pacific Integrated Model
ANEMI	An Integrated System Dynamics Model for Analyzing the Behavior of the Social-Energy-Economic-Climatic System
ASAM	Abatement Strategies Assessment Model
BAU	Business as Usual
BESOM	Brookhaven Energy System Optimization
BP	British Petroleum
BUEMS	Boğaziçi University Energy Modeling System
BUENAS	Bottom-up Energy Analysis System
CASM	Climate Change Assessment Model
GDTC	General Directorate of Turkish Coal
CES	Constant Elasticity of Production
CETA	Clean Energy Technology Association Model
CGE	Computable General Equilibrium Model
CH_4	Methane
CIMS	Canadian Integrated Modeling System
CO	Carbon Monoxide
CO2	Carbon Dioxide
COAHRD	Hard Coal
COALIG	Lignite
COM	Commercial Sector
DICE	Dynamic Integrated Model of Climate and the Economy
E3ME	Energy-Environment-Economy (E3) Model
EFFECT	Energy Forecasting Framework and Emissions Consensus Tool
EFOM	Energy Flow Optimization Model
EFOM-ENV	Energy Flow and Optimization Model – ENVironment
EGC	Electricity Generation Company

ELC	Electricity
EMO	Institute of Electricity Engineering
ENDAM	Energy, EcoNomy, Environmental Damage Model
ENVEES	Energy-Economy-Environment Model
EOH	Ending Of Horizon
ERIS	Energy Research and Investment Strategies Model
ERU	Emission Reduction Unit
EPPA	Emissions Prediction and Policy Analysis Model
ESCAPE	The Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions
ETL	Endogenous Technology Learning
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
FUND	Climate Framework for Uncertainty Negotiation and Distribution
GASNGA	Natural Gas
GDSHW	General Directorate of State Hydraulic Works
GEM-E3	Global Energy Model
GREEN	Tool for Assessing the Life Cycle Climate Performance Model
GTAP	Global Trade Analysis Project
GTAP-E	Energy-Environmental version of Global Trade Analysis Project
HERMES	Harmonized European Research for A Multinational Economic and Energy System Model
HFC	Hydro-fluorocarbons
HGV	Heavy Good Vehicle
IAM	Integrated Assessment Models
ICAM	Integrated Climate Assessment Model
ICES	The Inter-temporal Computable Equilibrium System
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMAGE	Energy-Industry System Model
IND	Industry Sector
IO	Input-Output Models

IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
LEAN	Lean Management for the Energy Model
LEAP	Long-Range Energy Alternatives Planning System Model
LT	Light Truck
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curve
MAED	Model for Analysis of Energy Demand
MAED-D	Model for Analysis of Total Energy Demand
MAEDEL	Model for Analysis of Energy Demand For Electricity
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MARKAL	Market Allocation Model
MARKAL-ED	Market Allocation Model Combined with a Micro Model -Stepwise Demand Function
MARKAL-MACRO	Market Allocation Model Combined with a Macro Model
MARKAL-MICRO	Market Allocation Model Combined with a Micro Model
MCP	Mixed Complementarity Problem
MDM	Multi-sectoral Dynamic Model
MEDEE	Modele d’Evolution de la Demande d’energie
MEPA	Massachusetts Environmental Policy Act Model
MERGE	3 Integrated Assessment Model for Global Climate Change
MESSAGE	Model For Energy Supply Systems And Their General Environment
MIDAS	Multinational Integrated Demand and Supply Model
MINICAM	Mini-Climate Assessment Model
MIS	Macroeconomic Information System Model
MSW	Municipal Solid Waste
MURE	Mesures d’Utilisation Rationnelle de l’Energie
NEMS	National Energy Modeling System of USA
NIA	National Impact Analysis
NMVOC	Non-methane Volatile Organic Compounds
N_2O	Nitrous Oxide

NO_X	Nitrogen Oxides
NUKURN	Nuclear Power
OECD	Organization for Economic Co-operation and Development
OILCRD	Crude Oil
OILDSL	Diesel
OILDST	Distillate Fuel Oil
OILGSL	Gasoline
OILJTF	Jet Fuel
OILKER	Kerosene
OILLPG	Liquefied Petroleum Gas
OILRFO	Residual Fuel Oil
PAGE	Policy Analysis of The Greenhouse Effect
PFC	Perfluorocarbon
POLES	Prospective Outlook on Long-term Energy Systems
PRIMES	The Primes Energy System Model
PTC	Petroleum coke
QUEST	A Macro Econometric Model for EU Countries
RAINS	The Model of the International Institute for Applied Systems Analysis
REAPS	Resource and Energy Analysis Program
RIAT	Regional Integrated Assessment Tool
RICE	Regional Integrated Model of Climate and the Economy
RNWBIO	Bioenergy
RNWETH	Ethanol
RNWGEO	Geothermal Power
RNWHGN	Hydrogen Power
RNWSOL	Solar Power
RNWWND	Wind Power
RSD	Residential Sector
SCREEN	Hybrid Bottom-Up Computable General Equilibrium Model
SF_6	Sulphur Hexafluoride
SGM	Second Generation Model
SLICE	Stylized Integrated Assessment Model of Climate and the Economy

SOCAR	The State Oil Company of Azerbaijan Republic
SO_2	Sulphur Dioxide
SUPELC	Imported Electricity
TANAP	Trans Anatolian Natural Gas Project
TARGETS	Tool to Asses Regional and Global Environmental and Health Targets for Sustainability
TB	Transport-Bus
TC	Transport-Car
TETC	Turkish Electricity Transmission Corporation
TR	Transport-Rail
TIMES	The Integrated MARKAL-EFOM System
TIMES-MSA	Decomposed Macro Stand-Alone implementation
DBT	Development Bank of Turkey
TRN	Transport Sector
TURKSTAT	Turkish Statistical Institute
UDHB	The Ministry of Transport and Maritime Affairs and Communication
UNFCCC	The United Nations Framework Convention on Climate Change
WARM	World Assessment of Resource Management
WEM	World Energy Model
WIAGEM	World Integrated Assessment General Equilibrium Model

1. INTRODUCTION

Rapidly increasing population and developing industries increase the demand in energy. Using limited natural resources is not only plays a strategically but also politically important role as the gap between energy production and consumption continues to grow.

Energy is an important aspect of our national economy. Nations and international corporations are racing to obtain access to energy resources such as petrol, natural gas, coal, etc. Energy is the main keystone of industrialization and an irreplaceable aspect of daily life. Hence, energy demand is a constant trending topic on both national and international spotlight.

The fact that energy resources can diminish, the existence of foreign dependency, and environmental factors, producing safe, substantial, cheap and clean energy for countries is among the basic problems of economic and social life. With a rapidly increasing population and industry, energy demand constantly increases in Turkey. Thus, the efficient use of energy, as well as harnessing the potential of alternative and renewable energy sources, are of utmost importance.

Energy, which is required to meet the basic needs of people and sustaining development, is used mainly in industries, residential areas, and transportation. On the other side, energy is also one of the main reasons of pollution during its production, cycle, transport and consumption.

This concept, forces scientist, to re-evaluate energy transformation tools and to develop new methods to better harness energy from limited sources. Due to political developments in the world, the energy prices are constantly increasing. In addition to this fact, the fossil fuels are of limited supply, and its production is costly. That’s why, the alternative energy resources should be determined and should be used efficiently.

The challenge for policy makers is mainly two-fold. First, is the effective use of limited natural energy sources. Second, is sustaining the emission from fuel consumption within controllable levels.

Upon realizing the severity of energy situation, countries started to act as a platform in a collaborative effort. The United Nations Framework Convention on Climate Change (UNFCCC) was established as a result of this endeavor in 1992. UNFCCC regard the developed countries as responsible for the current GHG emissions in the atmosphere. The Kyoto Protocol to the UNFCCC adopted in 1997 so as to create binding targets to secure the World future. Later on, UNFCCC in 2004 and the Kyoto Protocol were ratified by Turkey in 2009 (TURKSTAT, 2013).

For the case of Turkey, statistics reveal that our national primary energy consumption increased at a 5.1% annual growth over the course of 50 years (Kumbaroğlu, 2003). The most sensitive spot of the statistics is that GHG increased 124% in 2011, compared to the 1990's value. Another punch line is that energy sector incurs 86% of the CO2 emissions (TURKSTAT, 2013).

In the light of this information, the management of carbon emission issue and the selection of appropriate clean energy technology at national scale can be considered as a key issue. Various studies on environmental impacts of energy use for the case of Turkey, accentuate the rapid growth of pollutant emissions and reveals that national policy makers are in urgent need of an appropriate modeling methodology that could give accurate projections on future forecasts (Kumbaroğlu, 1997; Demirbas, 2003).

Contrary to the expectations, there exist no commonly accepted energy-economy-environment model that gives safe estimates on the future projections of Turkey. This thesis aims to fulfill this gap by introducing a large-scale integrated modeling for the national energy system. The interaction among economic activity, energy consumption, and their effects on climate change can be estimated using the proposed model.

To respond the need of energy and environment modeling for Turkey, the primary purpose of this dissertation is to provide the groundwork for a sustainable energy future in

Turkey. The developed model not only represents the reaction of system to interventions of policy makers on the market, but also creates a convenient environment for decision makers to evaluate their investments better. Proposed model is a useful data source for each and every investor/user within the energy production, transmission, and production chain. It is also suitable for technology evaluation in consumption channels as it includes industry, commercial and residential, transport and agriculture sectors in addition to electricity production sector.

This dissertation has two main goals. First of which is building an integrated energy model representing all demand industries and Turkish energy industry within the TIMES modeling system. Second and even more important one is building the Boğazici University Energy Modeling System (BUEMS). A modeling system will be constructed with open formulations, enabling all investments in Turkish energy industry can be optimized in an integrated manner. A conceptual framework energy-economy-environment model was developed to provide a deeper understanding of interrelationships between energy, the economy, and the environment. The thesis includes results of TIMES_TR and BUEMS_TR models. Additionally, model building, determining data requirements, data collection, base year calibration, changes in the Turkish energy system in last decade are explained in detail.

This dissertation is a comprehensive resource examining Turkish Energy System as it not only includes BUEMS modeling system, but also TIMES_TR and BUEMS_TR model results and the change energy system has faces.

The following section contains the literature survey in which the classification of different modeling methodologies and their application areas are represented. The third section illustrates working mechanisms of TIMES modeling systems. The fourth section explains how the BUEMS modeling system was built in detail. The fifth section narrates the BAU scenario results and other findings that were calculated for Turkey using TIMES and BUEMS modeling systems. In the last part, a general evaluation about status quo in Turkey, and results and suggestions are presented.

2. ENERGY-ECONOMY-ENVIRONMENT MODELING LITERATURE REVIEW

BUEMS modeling system that has been proposed in the thesis, is viewed under energy-economy-environment class in literature. These kinds of models vary depending on their target group (policy makers, scientific and research communities), intended use (data analysis, forecasting, simulation, optimization, estimation of parameters, etc.), regional coverage (regional, national, global), conceptual framework (top-down, bottom-up) and available information (Herbst *et al.*, 2012).

In this section, models that has been proposed to date are investigated, while the advantages and disadvantages of current energy-economy-environment models are examined in order to create a basis for BUEMS model, and where it should be categorized.

As a result of the tremendous diversity of these models, the question arises about which model is the most suitable for a given specific purpose. Moreover, different models have different characteristics that are important to take into account when interpreting the results that gathered from them. A classification scheme can be a beneficial way of providing insight into the working mechanism of the energy models considering their concordance and discordance, and answering the question that previously mentioned.

One of the main classifications is conducted by Hourcade *et al.* (1996). He puts forth a classification method that considers three important aspects including the purpose, the structure and the assumptions of them (Beeck, 1999).

A further classification method is conducted by Grubb *et al.* (1993). They introduce six different dimensions to categorize energy-environment-economy interaction models including their main modelling structure (top-down, bottom-up), time horizon set by the model, the sectoral coverage of them (focusing on only one sector or evaluates multiple of them), optimization-simulation techniques, a level of aggregation, geographic coverage, trade, and leakage.

There are two broadly accepted approaches for modeling energy-economy-environment interaction according to the level of aggregation as bottom up and top down.

These two methodologies have a basic difference in the structure of the representation of technologies that belong to the energy system and the theoretical description of the rest of the economy. The models that belong to the former group are purely partial models that only focus on energy sector, in which interaction with other economical entities are not taken into consideration. The latter, namely top-down models, describe the energy system in a highly aggregated way using neoclassical production functions (Löschel, 2002).

Due to the shortcomings of bottom-up and top-down modelling structures, recent studies revealed the necessity of combining the two modeling approaches called hybrid models that contain the detailed representation of energy with rich technological base of bottom-up models with the economic extensiveness of top-down models were developed (Proença and Aubyn, 2009).

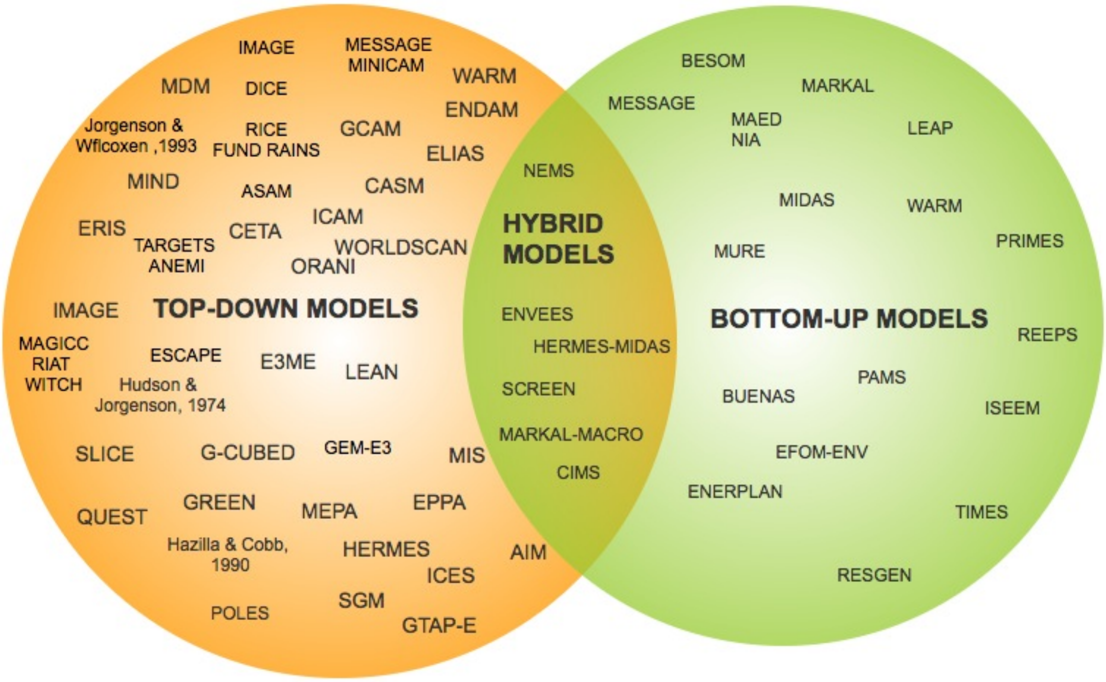


Figure 2.1. Energy model classification according to the modelling approach.

As it can be seen from Figure 2.1, in the literature, there have been numerous models, which can be classified under these top three headings.

Moreover, each field is divided into well-accepted sub-classes. In the following section three main classes according to the type of modeling approach will be explained briefly as; Top-down, Bottom-up, and Hybrid. The sub-classes under these main approaches are constituted as of Figure 2.2 (The commonly used models and their classification will be listed in Appendix A).

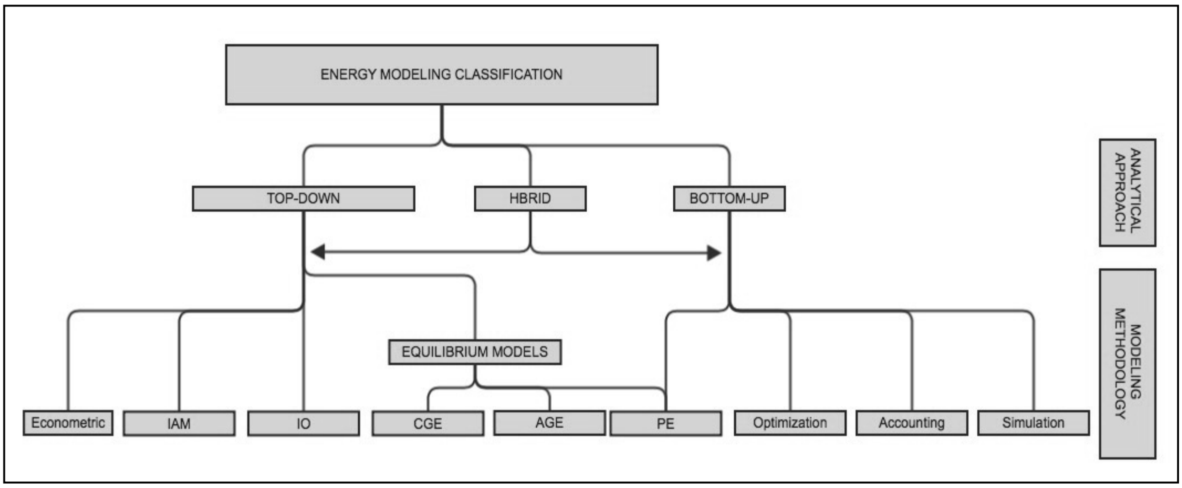


Figure 2.2. Energy model classification table.

2.1. Top-Down Models

In top-down models, aggregate economic variables are used to evaluate the system. The term “top” is used to denote the aggregate models, whereas “bottom” stands for the disaggregated models.

Top-down models can be considered as economic type models that rely on the mechanism, which uses parameters to estimate aggregate relationships between costs, the inputs and outputs to an economy in an equilibrium framework (Jaccard and Rivers, 2005).

Moreover, this kind of models is not capable of representing the advanced technological innovations. As a result of it, top-down models reveal that the efforts of changing the energy system from the current structure would be excessively costly which means they overestimate the economic adjustments and cannot evaluate the possible technological changes (Hourcade *et al.*, 2006).

The modeling methodologies that are classified under top-down approach can be listed as; Input-Output Models, Integrated Assessment Models, Computable / Applied General Equilibrium Type of Models and Econometric Models. The detailed information about the modeling methodologies as can be seen from Figure 2.3;

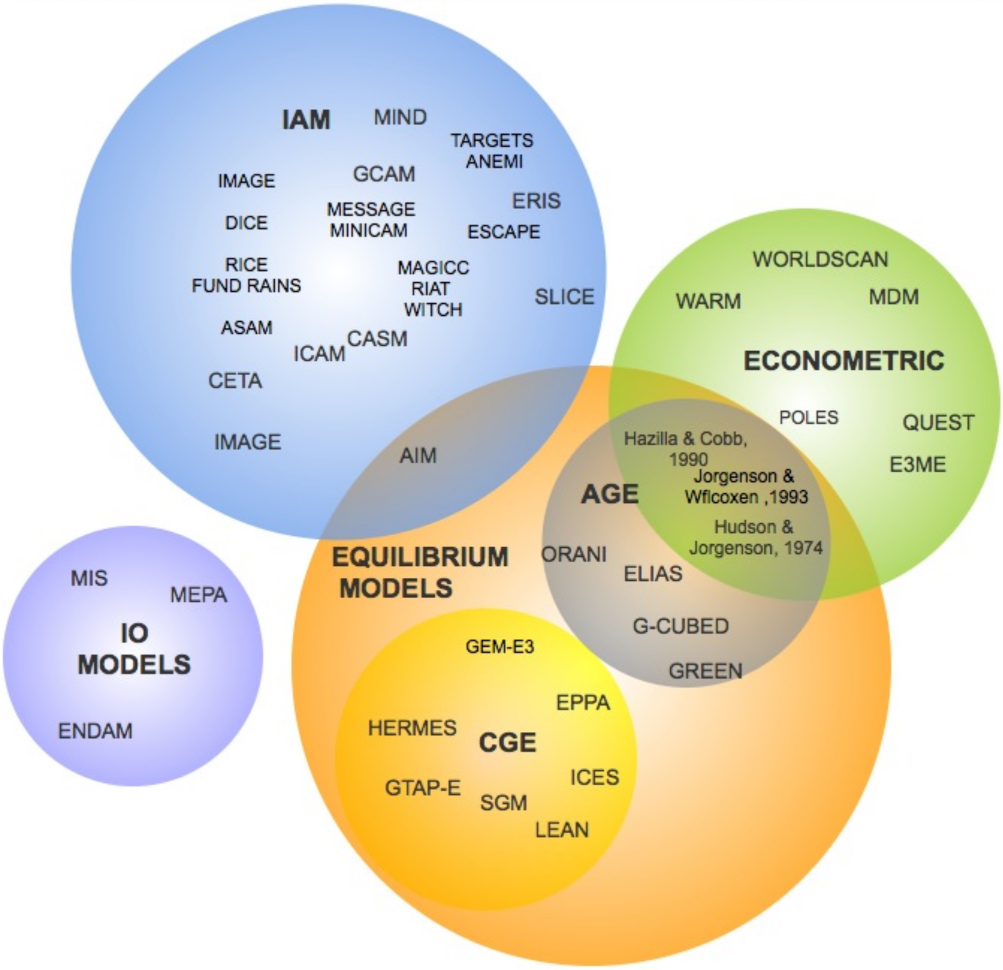


Figure 2.3. Top-down model classification scheme.

2.1.1. Input-Output Models (IO)

Input-Output model was developed by Wassily Leontief and earned him win a Nobel Prize in the field of Economic Science. In this model, the economic structure that defined regarding sectors is represented as linear equations.

In this kind of model, a detailed description of the economic structure is obtained by the model feature, which captures sector-based intermediate, final demand, and primary input requirements. Moreover, the model can give information about the relationship between the level of economic activity and its corresponding impact on the environment (Cruz, 2002).

IO models are the most widely utilized approach for investigating not only the direct economic and sectoral effects of demand-driven policies but also indirect effects on the economy (Pollin *et al.*, 2009) and for making conditional projections investigate the impact of a particular change.

Beside their advantages, primitive IO models are criticized for their range of application, for the reason that they can only be applied at national scale. Furthermore, they are not able to cover substitution and feedback mechanism between energy demand and supply (Kemfert, 2003).

In spite of their disadvantages, they have formed the basis of energy-environment modeling for many years, nay IO models still maintain its popularity. In recent years, there have been numerous studies that utilize input-output techniques (Turner *et al.*, 2007). Such as the study of Zhang *et al.* (2013), an input-output modeling is carried out to reveal domestic trade impacts on the energy consumption for the case of China. By that way, demand-derived energy requirements for the regional economies are investigated from the regional and sectoral insights.

Additionally, Zhoua *et al.* (2010) provide a detailed calculation of natural resources and environmental emissions at urban scale by utilizing the economic input–output analysis. The issues addressed in this study consist of; GHG emissions, water supply energy, solar energy and cosmic energy for the case of Beijing.

As the awareness of global warming increased, EU Commission has developed some restrictions. In the study of Markaki *et al.* (2013), they applied IO analysis to satisfy energy and environmental targets that belong to the field of climate change set by European Commission. Their aim not only to calculate the investments in industry sector but also to observe impacts of the pre-set enhancements on production and employment at a macro level in their domestic economy. To meet their aims, the input–output analysis has been carried out. The case specific data such as the implementation of energy conservation measures; renewable energy technologies' promotion levels are also added to the model.

There have been various models, which utilize input-output analysis such as MIS (Macroeconomic Information System) (Kemfert and Kuckshinrichs, 1995), ENDAM (Hawdon and Pearson, 1995) and MEPA (Stevens *et al.*, 1981). The model specific structures and their capabilities are given as follows;

ENDAM (Energy EcoNomy Environmental Damage Model) was developed for the case of the UK, investigates both energy and non-energy sectors. Coal, refinery processes and electricity generation are added to the model as energy industries, besides agriculture sector, construction sector, industry sector and transport are included as non-energy sectors. Due to reveal a detailed projection of environmental emissions, sulfur dioxide, nitrogen oxides and CO2 are added to the model. With the data mentioned above the model aims to explore the sectoral interrelationships considering their energy consumptions and related environmental concerns to evaluate and make a selection of the alternative energy-environmental policy questions that point of concern. To this end, some macro level economic problems are taken into account (Hawdon and Pearson, 1995).

2.1.2. Integrated Assessment Models (IAM)

In the literature there are various definitions of Integrated Assessment Models. One of the commonly accepted definitions is belong to Kelly and Kolstad (1999). They define an integrated assessment models as "any model that combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control".

Löschel (2002) divides IAMs into two broad categories; policy evaluation IMAGE (Energy-Industry System Model) and policy optimization DICE (Dynamic Integrated Model of Climate and the Economy) to find the optimal policy strategies (Akhtar *et al.*, 2013). Whereas Weyant *et al.* (1996) classifies integrated assessment models into three according to their purposes including the evaluation of the policies concerning climate change.

Moreover, Davies and Simonovic (2011) mention that integrated assessment is a useful tool to structure knowledge and characterize uncertainty and to observe feedbacks between components of a large system as in the case of policy on energy and environment.

Serving as tools for communication on complex scientific issues, their capability of exploring interactions and feedbacks that make possible to investigate the relational insights that most of the disciplinary studies cannot offer can be considered as the strength of IAMs (Martens, 2003).

In recent years, integrated assessment models have been preferred as a useful tool on account of this they have been widely utilized to analyze the energy and environment relationship (Laniak *et al.*, 2013; Akhtar *et al.*, 2013). DICE (Nordhous, 1994), RICE (Tol, 1999), AIM (Matsuoka *et al.*, 1995), FUND (Bareto and Kypreos, 2000), RAINS (Alcamo *et al.*, 1990), CETA (Batjes and Goldewijk, 1994): MERGE (Manne *et al.*, 1995), ASAM (Warren and ApSimon, 1999), ICAM (Dowlatabadi, 1998), CASM (SEI, 1991), MESSAGE (Schrattenholzer, 1981), IMAGE (Rotmans, 1990) are some of the integrated assessment models that dominate the literature. Furthermore, recent studies try to utilize IAMs by integrating multiple techniques as in the case of Richards *et al.* (2013), they incorporate Bayesian Belief Networks for climate change problem of Australia.

IAMs have a broad range of usage in the context of environmental, social and economic interactions modeling. Since environmental issues have diversified sub-fields, IAMs can also apply to the individual cases such as water and air quality issues. ANEMI (Davies and Simonovic, 2010), TARGETS (Rotmans J and de Vries, 1997) and WorldWater (Simonovic, 2002) are the examples of IAMs that concerns with the case of water quality. Moreover, The MAGICC model that aims to incorporate ocean heat transport (Meinshausen *et al.*, 2008), and RIAT developed by Carnevale *et al.* (2012) that assess air quality issues prove that IAMs have widespread usage.

Besides its popularity, IAMs are criticized with their limitations and weaknesses. One of them is related to their underlying theory. IAMs mostly rely on a neoclassical theory of economic growth and its adequacy for long-term global change assessment is still a debate topic. Additionally, these types of models do not concern with some features such as concentration of market power, wealthy and poor inequality in the market, etc. (Giupponi *et al.*, 2013). IAMs are criticized with their high level of data integration and limited calibration qualifications that is not capable of handling stochasticity (Martens, 2003).

ANEMI (An Integrated System Dynamics Model for Analyzing Behavior of the Social-Energy-Economic-Climatic System) modeling approach is developed by the University of Western Ontario, Canada. This model uses a system dynamics simulation approach and investigates the feedback effects of various water resources policies, such as wastewater treatment, irrigated agriculture, etc. (Davies and Simonovic, 2011). As a benefit of using dynamic system approach, ANEMI can model nonlinear feedbacks within the energy environment modeling for the case of water resources.

MINICAM (Mini-Climate Assessment Model) is known for the rich description of the energy system with detailed representation of the most important greenhouse gasses and absorbing aerosols together (Hedenus *et al.*, 2013).

MINICAM is a well-rounded model that aims to reveal the dynamics of human climate interaction concerning emissions that result in global warming (Scott *et al.*, 1999).

After the presentation of MINICAM, researchers attempted to improve the model to make it capable of dealing with policy outcomes under uncertainty. Michael J. Scott *et al.* (1999) have added a stochastic simulation feature to MINICAM 1.0 by that way the sources of uncertainty can be manageable, so the model turns into a useful tool to guide the strategies for coping with uncertainty (Jebaraj and Insiyan, 2006).

DICE (The Dynamic Integrated model of Climate and the Economy) family of models is developed to investigate the climate change by viewing the economics of climate change from neoclassical growth theory perspective. In this point of view, future consumption is fueled by the capital, education, and technology investments by economic agents (Ortiz and Markandya, 2009). It is assumed that social welfare function defines the preferences of the world by ranking different consumption paths, taking economic and geophysical relationships as boundaries. DICE model aims to optimize the consumption considering an objective function that aims to maximize total social welfare. The efforts to improve DICE model still continues. As in the study of William Nordhaus, he added uncertainty in climate sensitivity and climate damage to the parameters of concern to his already ongoing research for uncertainty in emissions (Scott *et al.*, 1999).

WITCH (The World Induced Technical Change Hybrid) model analyzes optimal climate mitigation policies, using a game-theoretical framework. In this top-down model, the world is composed of twelve macro regions, where the welfare function is maximized by a social planner (Bosetti *et al.*, 2006).

2.1.3. Computable and Applied General Equilibrium Models

In computable/applied general equilibrium (CGE/AGE) approach optimization methods are utilized to identify the energy supply and demand functions (Akhtar *et al.*, 2013).

General equilibrium models enable evaluating interactions between the energy system and the rest of the economy considering monetary terms (Löschel, 2002). By that way, the impact of carbon abatement policies on fossil fuel consumption and their indirect effects on other markets can be investigated. There are two main approaches under general equilibrium modeling class namely, CGE and AGE. They both utilize the main theory of general equilibrium but differ with the underlying approach. Arrow–Debreu general equilibrium theory underlies the structure of AGE models that work in a different manner than CGE models. The existence of equilibrium is gathered via the standard Arrow–Debreu exposition then solves for market-clearing price vector using Scarf's Algorithm. On the other hand, CGE models consist of macro balancing equations, and unknowns solvable as simultaneous equations (Smale, 1981). In the literature, CGE type of models is more popular than AGE models. As a result of it, the characteristics of CGE models is given in a detailed way. They include a detailed set of equations that define economy sectors on aggregated production functions and consumers' utility functions (Ortiz and Markandya, 2009).

CGE models are based on conventional economic theory. As a result, they are also able to represent real-world macroeconomic responsiveness to policies to identify the orders of magnitude, of the resulting economic effects (Allan *et al.*, 2007).

Additionally, CGE models simulate markets for each factor of the economy such as production function with nested constant elasticity of substitutions (CES), household preferences, and foreign exchange, with supply and demand equations (Nakata, 2004).

There are two major advantages of using CGE models when estimating pollution costs. Firstly, they not only describe the economic dynamics but also change in the resource labor, leisure and demands but also analysis of multiple scenarios is allowed (Nam *et al.*, 2010).

Besides its advantages, comprehensive data requirement makes CGE models hard to apply (a set of multi-sectorial accounts together with a broad range of behavioral and technical parameters is needed). Nevertheless, there are various applications of CGE/AGE type of models in the literature such as: ICES (Ortiz and Markandya, 2009), GREEN (Burniaux *et al.*, 1992), GEM-E3 (Hedenus *et al.*, 2013), HERMES (Bossier *et al.*, 1998), AIM (Masui *et al.*, 2006), SGM (Fisher *et al.*, 1993).

GEM-E3's weakness can be considered as the lack of energy technologies' representation. The model is suitable for evaluating the impact policies in the economy for short-term, but it fails to get long-term analysis (Hedenus *et al.*, 2013).

Within the Global Trade Analysis Project (GTAP), an applied model is developed, namely GTAP-E by some additional enhancements on energy and technology (Wang and Nijkamp, 2007). It includes 37 industries in 20 countries in 10 regions. It is assumed that there exists only one traded commodity that can be considered to be a domestic product for each region (Ortiz and Markandya, 2009). Additionally, the welfare of regions is given by a Cobb-Douglas function.

GREEN (GeneRal Equilibrium ENvironmental) is a recursive-dynamic global AGE model that focuses on energy production and consumption. It is developed by the OECD Economics Department. It took 1985 dataset as a base and dynamically calibrated allowing saving decisions to affect economic outcomes of future periods utilizing the accumulation of capital (Burniaux, 1992).

There are 12 regional sub-models (four of them is OECD, and the remaining regions are non-OECD countries) representing global economic activity, and each of them is modeled similarly but using different base data and parameter sets (Nakata, 2004). Also, it captures 11 producer sectors accompanying with four consumer sectors.

GREEN model linked the regions mentioned above through trade flows, and the production side of these regions has a detailed description of it (Burniaux, 1992).

ICES (The Intertemporal Computable Equilibrium System) is an extension of the GTAP-E model, so it also uses the GTAP database. It's a recursive dynamic general equilibrium model, using eight regions of the world and 17 production sectors. It encompasses a time frame of 1997 to 2050 (Ortiz and Markandya, 2009).

HERMES (Harmonized European Research for Macro-sectorial and Energy Systems model) is another CGE model utilizing CES and Cobb-Douglas types of production functions (Karali, 2012). It was developed upon request of European Commission (DGXII project) (Italianer, 1986). This model attempt to evaluate the market effect of carbon taxation and the emission of greenhouse gasses (Zang and Folmer, 1998). Hermes is an econometric model, which work for short to medium term evaluations (2 to 8 years).

HERMES is capable of concerning eight forms of energy, namely; coal, coke, crude oil, petroleum products, natural gas, derived gas, electricity, other energies. By investigating the general characteristics, HERMES enables trade flow that includes Japan USA and 12 EU countries; also it contains 15 categories for households' consumption (Bossier *et al.*, 1998).

AIM (The Asian Pacific Integrated Model) is a model for greenhouse gas emissions' scenario analyses that reveal the impacts of global warming. Asian-Pacific Integrated Model that utilizes dynamic optimization technique is a multi-region model, which composed of Japan, China, USA, OECD countries, Russia, and Rest of the World with a multi sector global model (Masui *et al.*, 2006).

The AIM comprises two primary models, the former used to predict greenhouse gas emissions and the latter is to estimate their effect on global warming (Matsuoka *et al.*, 1995).

SGM (The Second Generation Model) is another example of the computable general equilibrium model class of energy, economy, and environment modeling. SGM that developed by Edmonds *et al.* (1995) consists of 14 world regions with nine producing sectors. Non-energy related greenhouse gas emissions are not considered by the SGM model (Fisher *et al.*, 1993).

2.1.4. Econometric Models

Econometric models are comprised of econometrically estimated equations that do not consider equilibrium assumptions. Models of this kind include an economic structure in a detailed way (Löschel, 2002). Econometric models can procure more accurate projections for short-term analysis, rather than bottom-up models (Loulou *et al.*, 2005). Econometric models are criticized for its inability to handle fluctuations in price that occur suddenly (Kumbaroglu, 2002).

POLES (Prospective Outlook on Long-term Energy Systems) model has a detailed representation of the global energy system, with the of end-use representation technologies (Hedenus *et al.*, 2013). It provides not only energy supply but also demand-side scenarios under a hierarchical system of sub models. POLES is eligible for long term analysis with the coverage of both national and regional assessments (Nakata, 2004).

E3ME (Energy-Environment-Economy Model for Europe) is another econometric model that is valid for 14 regions of Europe (east and west of Germany, north and south of Italy are assumed to be four different regions together with 12 EU member states).

This model utilizes econometric methods specified for the short term and medium term analysis. It is also capable of addressing the long-term effects of policies such as the ones that deal with the supply side of the labor market. EM3E uses 19 sets of disaggregated time-series econometrics equations with dynamic relationships.

As an advantage of EM3E, it has a detailed representation of economy by those way relatively complex scenarios, which is customized for each sector on country basis can be represented. As an example of econometric grounding models, it performs more accurately for short to medium term. As a result of further studies, Energy-Environment-Economy Model of the Globe (E3MG) is generated as the developed version of E3ME (Barker *et al.*, 2006)

QUEST (A Macro-Econometric Model for EUC Countries) can be regarded as a neo classical-Keynesian type of model that is capable of working for short to long term. The equations that embedded to the QUEST dynamic structure that seeks for an optimal solution (which maximizes utility and profit functions) (Roeger and Veld, 2004).

2.2. Bottom-Up Models

Bottom-up models include a partial equilibrium representation of the energy system, describing it in great detail. They are generated with high technological detail even cost structures of future technologies (Böhringer and Rutherford, 2008). Bottom-up models try to find the least-cost combination of energy technologies to meet energy demand that restricted by technological availability, a potential of energy sources, emissions, etc.

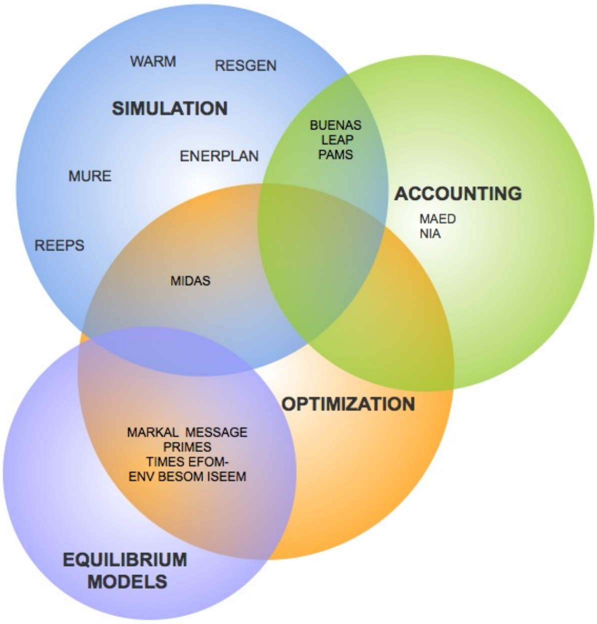


Figure 2.4. Bottom-up model classification scheme.

Bottom-up models are not capable of observing the interactions of the energy sector with the rest of the economy. Moreover, only the specific cost elements of economic agents are represented in this kind of models.

Different methodological approaches have been used in bottom-up energy-economy models. There is three commonly accepted methodological categories in the literature as simulation, optimization and accounting models (Mundaca *et al.*, 2010).

2.2.1. Simulation Models

These models are used to observe the microeconomic behavior which does not seek to reach optimal or rational pattern. They simulate the behavior of consumers and producers under various conditions. This kind of models tries to reveal the end user behavior for technology choice while considering various drivers (e.g., energy security) (Mundaca *et al.*, 2010).

2.2.2. Optimization Models

Optimization models aim to find least-cost solutions while considering technology configurations of energy systems based on various constraints (e.g. a CO_2 emissions target). MARKAL (Fishbone and Abilock, 1981), TIMES (Kumbaroğlu and Madlener, 2003), EFOM-ENV (Broek and Linden, 1992), MIDAS (Capros *et al.*, 1990) and PRIMES (Hedenus *et al.*, 2013) are some of the most popular energy environment modelings.

MARKAL (MARket Allocation) is a widely applied cost optimization linear programming model (Loulou *et al.*, 2004). It uses a bottom-up modeling approach under partial equilibrium methodology that also take accounts of the energy system with endogenous technological learning (Rafaj and Kypreos, 2007).

The standard MARKAL was developed as a demand-driven model by Members of International Energy Agency and Energy Technology Systems Analysis Program as a large-scale energy model for the medium and long-term analysis in 1980’s (Ramachandra, 2004). It is known as the developed version of the Brookhaven Energy System Optimization Model

(BESOM) (BESOM aims to reveal the most efficient resource allocation only at the national level).

MARKAL is a partial equilibrium model (Howells *et al.*, 2011). It aims to reveal the optimal set of technology to satisfy the total demand for energy within the pre-set period. It assumes there exist a perfect competition in the market that is of concern. MARKAL are composed of objective function (which is the total discounted system cost) and related constraints (Ramachandra, 2009).

ETSAP has developed the newer versions of MARKAL with additional specifications such as; MARKAL-MACRO, MARKAL-MICRO, Elastic Demand MARKAL, Elastic Demand MARKAL with Income Elasticity, Stochastic MARKAL, MARKAL with Endogenous Technology Learning (ETL), MARKAL with Environmental Damages, Multi-Region MARKAL with Bilateral and Global Trade, SAGE variant of MARKAL, Enhanced Refinery Blending variant of MARKAL, Lumpy Investment variant of MARKAL, Goal Programming variant of MARKAL (Noble, 2004).

TIMES (The Integrated MARKAL-EFOM System) can be considered as a developed version of MARKAL model generated by the Energy Technology Systems Analysis Programme (ETSAP) (Fishbone *et al.*, 1983; Berger *et al.*, 1992). The functionality of the model is extended by adding new features to the exploration of energy systems (Loulou and Labriet, 2008). As an example, the new inter-regional linkage feature on carbon mitigation of TIMES, allows the modelers to evaluate the effects of carbon permit trading (Goldstein and Greening, 2013). As a result of their flexible structure, MARKAL and TIMES are two of the most popular bottom-up models that have been preferred for a diversified range of studies in more than 80 institutions in 50 countries (Loulou *et al.*, 2005).

TIMES modeling approach provides solutions for not only for national scale but also for multi-regional scale over long-term, multiple period horizons (Loulou and Labriet, 2008). As in the general structure of bottom-up modeling, TIMES provides a technology-rich basis for the analysis of both a single sector and the entire energy sector to select the optimal (less costly) technology alternative while satisfying the constraints (Jia *et al.*, 2011).

PRIMES (The Primes Energy System Model) concerns with the European energy system. Representation of end-use technologies and costs of new technologies can be considered as the strength of PRIMES (Hedenus *et al.*, 2013). It is designed to be an energy policy analysis tool that includes energy policy and technology assessment relationships.

EFOM-ENV (Energy Flow and Optimization Model – ENVironment) modeling framework was developed by European Commission to give solutions to the energy problems on a national scale. The primary assumption is that there exists no interaction apart from energy sectors. This model works for national scale and concerns with the medium to an extended period and aims to find the most appropriate environment policy analysis that results in emission reduction (Beeck, 1999). It optimizes the development of energy producing and consuming sectors taking the fuel import prices, useful energy demand into consideration (Nakata, 2004).

2.2.3. Accounting Models

The primary function of accounting models is to manage data and results. Accounting models describe the physical flows of energy. They often use spreadsheets. Models that belong to this class, rather than simulate the behavior of a system in which outcomes are unknown, require modelers to determine outcomes beforehand (Mundaca and Neij, 2010). The modeler introduces the expected future outcomes for each factor, so the performance of consistency belongs to the success of the modeler (IAEA, 2006).

Although there exist models that have only accounting framework such as; (Hainoun *et al.*, 2006), National Impact Analysis (NIA), some other models who prefer to combine accounting with other class such as simulation. As an example, LEAP (Lazarus *et al.*, 1995), BUENAS (McNeil *et al.*, 2008) and PAMS (McNeil *et al.*, 2006) are the models all of which belong to accounting and simulation type of energy-economy-environment modeling.

MAED (Model for Analysis of Energy Demand) is another model with accounting framework that derived from the works of International Atomic Energy Agency (IAEA). The general working principle of the MAED methodology is the developed version of MEDEE, so it is also known as MEDEE-2. It can be classified as a bottom-up model that captures medium and long-term energy demand analysis as a result of the technological, demographic and socioeconomic framework (Hainoun *et al.*, 2006). The model consists of two modules, MAED_EL, and MAED-D. The former deal with the economic sectors and related sub-sectors and calculates the total energy demand, whereas, the latter only determined the total electric power demand for each hour of the year (Mundaca *et al.*, 2010)

LEAP (The Long-range Energy Alternatives Planning system) model was developed by the Stockholm Environment Institute at Boston. It is constructed with a bottom-up structure concerning energy-environment interactions, which utilizes accounting framework for forecasting at national and regional level (Lazarus *et al.*, 1995).

By looking it in a detailed way, LEAP makes energy system analysis that includes energy resources, generation, and distribution to end-use across the economy. Beside its ability to capture basic accounting relationships (e.g., energy demand and supply, atmospheric emissions), the modelers can make changes on the model to add new features including technology penetration into the market as a function of income level, technological costs and governmental interventions (Mundaca *et al.*, 2010).

2.3. Hybrid Models

As mentioned before, bottom-up models use partial equilibrium representation with highly detailed technology information, whereas top-down models contain an economy-wide perspective. Conventional top-down models are criticized with limited representation of the energy system while investigating the energy-economy interactions. Due to its nature, top-down models lack in technological options that are crucial for the accurate assessment of energy policy options.

Besides, bottom-up models fail to capture the macroeconomic feedbacks that occur as a result of different energy-climate policy instruments.

Due to the shortcomings of bottom-up and top-down models, recent studies revealed the necessity of combining the two modeling approaches. To satisfy this need, hybrid models that contains deep-technological detailed structure of bottom-up models with the economic explicitness of top-down models were developed (Proença and Aubyn, 2009).

Hybrid modeling is classified into three main branches according to the structure that combines top-down and bottom-up3 approaches. “Soft-link hybrid models” combine independent top-down and bottom-up models by using the output of former as the input of the latter. Another kind of hybrid model called Mixed Complementarity Problem (MCP). It treats two different approaches as a single integrated model. The third category of hybrid modeling includes the models that create a link on one model that access the reduced form of the other (Böhringer and Rutherford, 2008).

NEMS (Richey, 1998), MARKAL-Macro (Bhattacharyya and Timilsina, 2010) and MESSAGE-Macro (Messner and Schrattenholzer, 2000; Mundaca and Neij, 2010), ENPEP (Buehring *et al.*, 1991), ENVEES (Yang *et al.*, 1996), ETA-MACRO (Tol, 1997), HERMES-MIDAS (Dowlatabadi, 1998), SCREEN (Fisher *et al.*, 1993), CIMS (Nordhaus, 1994) are the examples of hybrid modeling. The detailed information about the selected hybrid models will be given as follows;

ENPEP (Energy and Power Evaluation Program) model is developed by the International Atomic Energy Agency (IAEA). The model includes a detailed analysis for electricity based on least cost optimization and it is possible for ENPEP to be used for energy policy analysis, energy tariff development, investment analysis which can be considered as crucial issues within environmental policy analysis (Beeck, 1999).

CIMS (Canadian Integrated Modelling System) originally is a hybrid energy-economy model, developed by the Energy and Materials Research Group at Simon Fraser University in Canada is composed of 7 regional sub-models (Goggins, N., 2005). CIMS model simulates the investment decisions in the market for each energy-intensive sector of the economic structure, so it attempts to describe the consumer behavior in the real world situations. This model is capable of handling about 2800 technologies across the 15 sectors of the economy (Melton, 2008). Moreover, macroeconomic feedbacks for a certain energy product or service are also taken into account by CIMS.

NEMS (National energy modeling system) (Hoffman and Stephan, 1996) is another example of the hybrid type of energy-economy model that provides projections of U.S. domestic markets undergrowth and policy scenarios in the long-term (a time horizon of about 25 years). NEMS combines optimization-simulation-accounting components to provide a general equilibrium to the system under concern (Mundaca and Neij, 2010).

The energy sector is covered with a rich technological representation of the energy sector. NEMS consists of four sectors of demand side as industry, transport, residential and commercial as well as supply side. There exist four modules for the supply side including oil, gas and coal supply accompanied by renewable fuels (Bhattacharyya and Timilsina, 2010).

MESSAGE-MACRO is another Hybrid model, which combines a bottom-up type (rich technology representation) systems engineering optimization model of MESSAGE with a top-down macroeconomic model (Messner and Schrattenholzer, 2000). This model composed of 11 regions as a representation of global energy system (Baretto *et al.*, 2003). In MESSAGE-MACRO hybrid model, energy demands are endogenously determined by the forecasted GDP and energy prices (Messner and Schrattenholzer, 2000)

MARKAL-MACRO model combines the bottom-up MARKAL model with MACRO model that is a macroeconomic model that includes an aggregate representation of energy services for long-term economic growth and other productive factors in the production and consumption (Tseng, 1996).

It aims to maximize consumer welfare over the pre-set period, optimize possible investments, which provide least-cost energy system configurations to meet endogenously determined demands for energy services.

3. THE TIMES FRAMEWORK

The TIMES model generator was developed by the International Energy Agency's (IEA) Energy Technology Systems Analysis Programme (ETSAP).

The TIMES is a modelling framework that is constructed to optimize the total discounted system cost while considering the set of constrains. It includes generic set of variables and equations that are able to generate a structure that represents an energy system for a specified country or region.

TIMES (an acronym for The Integrated MARKAL-EFOM System) is a model generator not only for a country, but also for multi-regional energy systems. TIMES system provides a technology-rich infrastructure to reveal the system behavior over a multi period time horizon. The system can include entire energy sector or a part of it (e.g. the electricity).

Using the end-use energy service demands (e.g. air travel, residential heating demand, iron and steel industry high temperature heat demand) and existing energy stocks (e.g. installed capacity of nuclear power plants, national available coal reserves) provided externally into the model, a TIMES model aspires to provide energy services with the possible lowest cost by concurrently taking into action (investment on eligible technology alternatives, decision making on energy trade and operating a bundle of power plants).

To form an estimate on future sources a TIMES model requires not only present sources and technologies that constitutes the energy sector but also future alternatives of them. Using the above-mentioned inputs, a TIMES model provides practicable and reliable investment choices based on the analysis of the system characteristics including the economic factors that belong to energy supply and generation technologies. Additionally, the scope of a TIMES model is not restricted to the monetary issues, environmental criteria are also taken into consideration (by identifying emission bounds or carbon prizing mechanisms) while providing least cost energy supply. By doing so, the model is suited to the observation of environmental policies.

The TIMES framework necessitates "sets" to specify the characteristics of the elements that generated energy system. There exist two main groups of sets; "user input sets" and "internal sets". The former includes the process or commodity groups that created to represent the characteristics and qualitative data. The latter already exists in the model to provide groups of specific classes (e.g. environmental parameters, renewable technologies). Two basic sets are defined in a TIMES model; commodities and processes. Commodities are divided into four main groups among themselves as depicted in Figure 3.1.

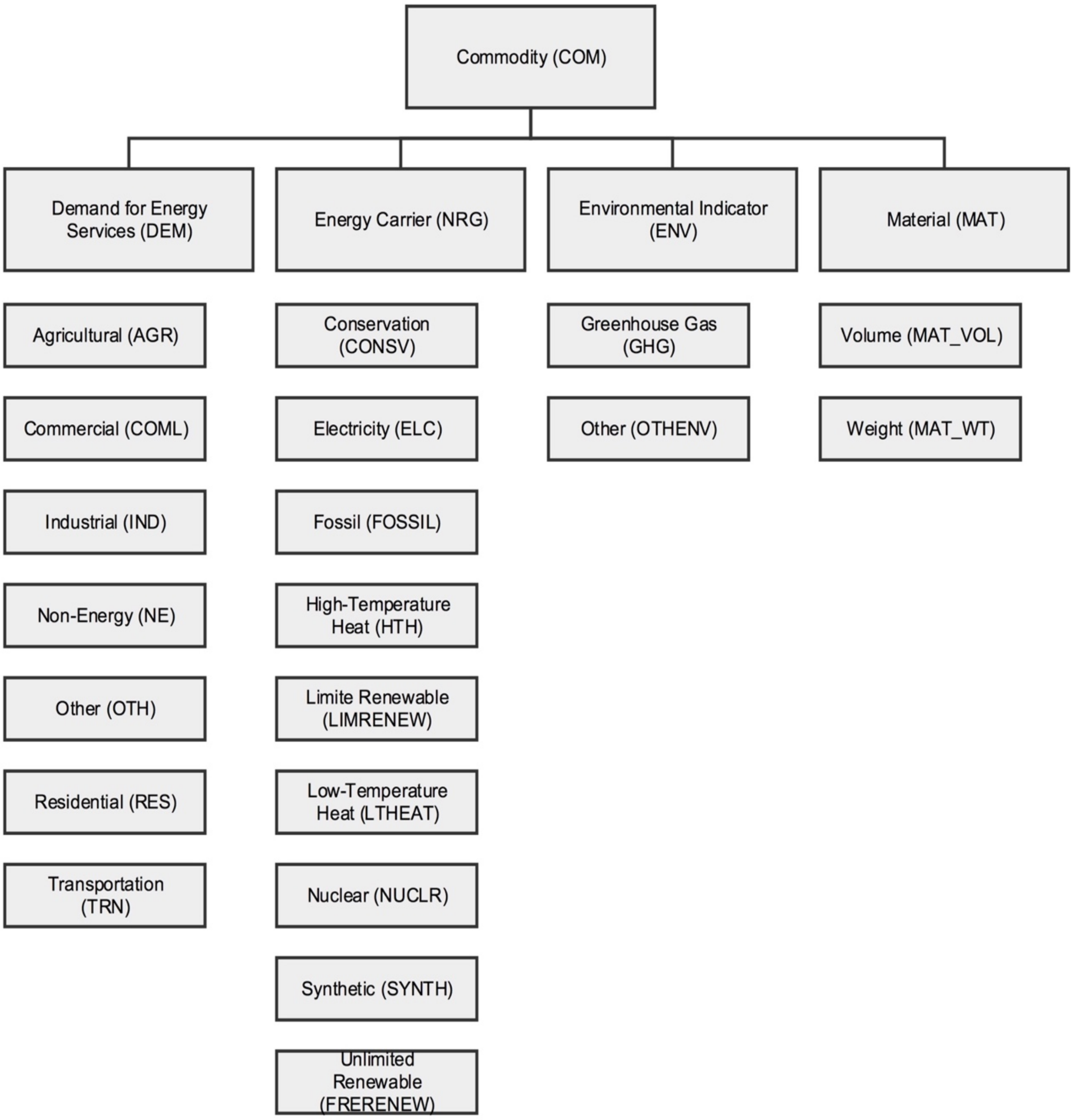


Figure 3.1. Set of energy carriers in the TIMES modeling framework.

3.1. The Set of Commodities

Each group is created for specific purpose. “Demand for Energy Services” commodity type stands for the end use demand sectors. For each sector there exists a sub-category. Within the TIMES modeling framework, associate information for each sector is stored into a model by means of commodities that belong to “demand for energy services” (e.g. for residential end use demand commodity, the unit is stored as billion lumens whereas for transport sector different unit (million-km-travelled) can be introduced into the model. On the other hand, “Energy Carrier” is a group consisting of all types of carriers that contain energy to be transformed to other forms (e.g. high temperature heat, low temperature heat, chemical operations and physical processes (travelled distance, lighting, cooling etc.)) during the modeling periods.

Another commodity group consists of “Environmental Indicators”, the commodities under this group is utilized by a TIMES model (To learn about the amount of greenhouse gas emissions resulting from the use of fossil fuels).

The fourth group is mainly used for energy resource extraction or importation/exportation processes. Two sub-groups denote the form of the matter (solid, liquid or gaseous) so that if a storage technology is defined into the model, the respective capacity can be arranged according to the form of considered matter.

3.2. The Set of Technologies

In the TIMES modeling framework, processes are used to define the energy technologies. Processes are classified under six different categories, e.g., Combined Heat and Power, Demand Devices, Electricity Generation Technologies, Energy Technologies, Heat Generation Technologies and Material Technologies.

The set of “Demand Devices” consists of end-use technologies that turns energy carriers into final energy demand to satisfy the set of “Demand for Energy Services” including agriculture, commercial, residential, industry, transport sectors and subsectors. As they require separate parameter groups structurally, a sub-classification is not needed. It is accepted that technologies in this set may be deployed at levels bounded by selected/ available capacities and in this manner the activity level is a function of capacity.

The set of “Electricity Generation” embodies the technologies that are able to generate electricity. They are introduced to the system with parameters including, availability, operating-maintenance cost, investment cost and new capacity investment cost. Additionally, what makes this set different is that, all parameters can be defined seasonal and daily basis. As an example, the capacity and availability of renewable energy sources vary from one-time slice (day-night, spring, summer, autumn, winter) to another.

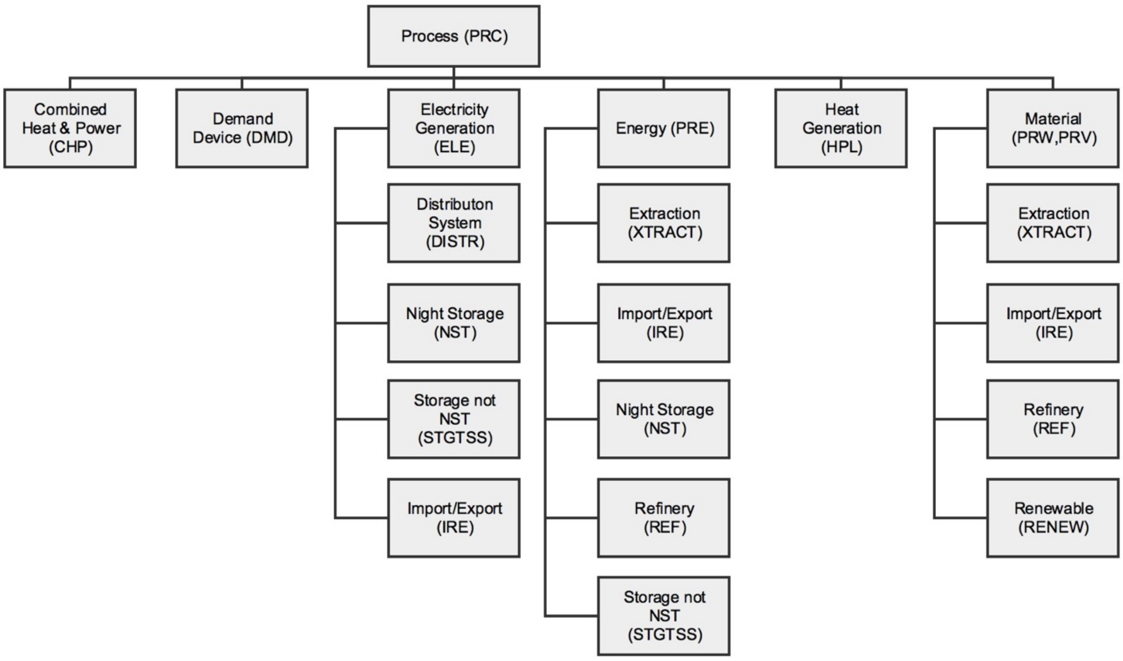


Figure 3.2. The set of technologies in the TIMES modeling framework.

The set of “Energy” includes all of the technologies that provide energy carriers into the system with a unit cost. Their working mechanism are similar to those of storage units. They do not necessitate any previous technology that gives a commodity to be processed. Their maximum total available capacity, annual procurement capacity and unit cost are set by the user. Commodities in energy carrier class can be defined in 5 different sub-categories as shown in Figure 3.2. Another way to define energy commodities in the model is to define them as “material” in the system. TIMES modeling framework already includes this option.

As given in Figure 3.2 Extraction, Import/Export and Renewable are the main subsets. Domestic extraction processes, e.g., hard coal, lignite mines, natural gas sources are defined under “Extraction” set of technologies.

For renewable resources, (e.g., solar, tidal, wind) although they are also domestic, since the unit cost and the availability factors during the year vary within the year, while resource levels are not depleted over time through usage, their qualifications differ from other sources of energy carriers. As a result, in the TIMES modeling framework the technologies that provide renewable energy sources into the system are group under this set.

Another main group is the “Import and Export” technologies. The former can be considered as another source of energy carriers into the system, whereas the latter regarded as a sink. Importation and Exportation make energy carrier trade possible in the model. So, if there exists an exportation activity then it has positive contribution to the system by providing income.

The TIMES modelling framework is designed to be employed on a long term time horizon that consists of several periods called milestone years. Each milestone year presents a specific year in which the model makes all decisions related to technologies, e.g. retirement of old capacity, making new investment, importation of a specific fuel types. So, it would not be wrong to say that each period should include a specific milestone year. In TIMES model, all of the variables related to both activity and flow is provided for the milestone year within each period.

3.3. Model Structure

3.3.1. Variables

Decision variables in the TIMES modeling framework consists of five different subcategories as given in Table 3.1. First set includes the process related variables. They provide information about the existing capacity levels and the technology investment levels. So the maximum available capacity for the considered period can be tracked.

Table 3.1. Variable definitions in the TIMES modeling framework (Loulou *et al.*, 2005).

Category	**Variable name**	**Brief description**
Process related	v ar_act	Annual activity of a process
	v ar_cap	Current capacity of a process, all vintages together
	v ar_ncap	Investment (new capacity) in a process
Commodity related	v ar_blnd	Blending variable (for oil refining)
	v ar_comnet	Net amount of a commodity
	v ar_comprd	Gross production of a commodity
	v ar_elast	Variables used to discretize demand curves
Flow (Process and Commodity) related	v ar_flo	Flow of a commodity in or out of a process
	var_ire	Flow of a commodity in or out of an exchange process (trade variable)
	var_sin/out	Flow of a commodity in or out of a storage process
Objective function related	v ar_obj	Variable representing the overall objective function (all regions together)
	invcost	Parameter representing the investments portion of a regional component of the objective function
	invtaxsub	Parameter representing the taxes and subsidies attached to the investments portion of a regional component of the objective function
	invdecom	Parameter representing the capital cost attached to the dismantling (decommissioning) portion of a regional component of the objective function
	fixcost	Parameter representing the fixed annual costs portion of a regional component of the objective function
	fixtaxsub	Parameter representing the taxes and subsidies attached to fixed annual costs of a regional component of the objective function
	v arcost	Parameter representing the variable annual cost portion of a regional component of the objective function
	elastcost	Variable representing the demand loss portion of a regional component of the objective function
	laterevenues	Parameter representing the late revenue portion of a regional component of the objective function.
	salvage	Parameter representing the salvage value portion of a regional component of the objective function
User Constraint related		

Another important issue related with the processes is to decide on the capacity utilization level. Operation level can be deduced by the annual activity level.

Another decision variable set is dedicated to commodities. They indicate the flow levels and the amount of maximum available commodity both for a specific period of time and whole planning horizon.

The flows can be traced on energy carrier level by utilizing commodity related variables, var_flo and var_ire ensures the commodity flow under technology breakdown.

Additionally, the objective function related variables provide the cost data that belong to any type of variable and fix cost values accompanied by taxes.

3.3.2. The objective function

In the TIMES modeling framework, the objective function is the sum of discounted value of net annual costs. As mentioned before, planning horizon consists of periods. At the end of each period system obtains costs and revenues resulting from some investment and fuel consumption activities. So the objective function covers discounted annual costs of each period.

Total discounted annual cost of a period is calculated by summing over all of the costs incurred due to the consumption and usage of model elements (fuel consumptions, technologies, demand segments, environmental variables etc.). Annual supply costs annualized investment costs, annual operation costs (including fixed and variable technology operation costs), minus revenue from exported energy carriers, plus taxes and emission costs are the components of total discounted annual cost.

In the TIMES modeling framework one general discount rate d(y) is introduced for the computation of the present value of the total system cost.

$$reg\_obj(z) = \sum_{y\in(-\infty,+\infty)} disc(y,z) \times\{invcost(y) + invtaxsub(y) + invdecom(y) + fixcost(y) + fixtaxsub(y) + varcost(y) - salvage(z)\} \quad (3.1)$$

where

- $reg\_obj(z)$: Discounted objective value (EQ_OBJ).
- $disc(y,z)$: Value, discounted to the beginning of year *z*, of a $1 payment made at beginning of year y, using general discount factor.
- $invcost(y)$: Equal to the portion of the cost objective for year y
- $invtaxsub(y)$: Equal to the portion of the cost objective for year y
- $invdecom(y)$: equal to the portion of the cost objective for year y
- $fixcost(y)$: equal to the portion of the cost objective for year y that corresponds to fixed annual costs.
- $fixtaxsub(y)$: equal to the portion of the cost objective for year y that corresponds to taxes and subsidies attached to fixed annual costs.
- $varcost(y)$: equal to the portion of the cost objective for year y, that corresponds to variable annual costs.
- $salvage(z)$: equal to the portion of the cost objective for region *r*, that corresponds to the salvage value of investments and other one-time costs. It is discounted to some base year y0.

3.3.3. Investment costs

Investment costs incurred due to the increments that results from the capacity change. The size of the increments affects the form payments. In the TIMES modeling framework large lump investments (investment on new nuclear power plant, new HTH facility for iron and steel production, etc.) and small investments (buying new refrigerator, air conditioning, etc.) are calculated differently with respect to the related streams of payments. Another issue related to the calculation of investment cost is the relative length of a project’s technical life. If the technical life of an investment is not large enough to cover a period (a period should be at least one year, but generally it is taken as five years) repetitive investments should be made all along the period. To cover the above mentioned cases four different investment cost calculation options are defined within the modelling structure. The formulations are provided in Equation 3.2, Equation 3.3., Equation 3.4 and Equation 3.5.

Case 1.a

$If\ ILED_t \ \leq ILED_{Min,t}$

$$\begin{aligned} invcost(y) = & \sum_{t \in milestone \cup pastyrs} indic(1.a) \\ & \times \sum_{v=\max\{m(t)-d(t)+1, y-elife_t+1\}}^{\min\{m(t),y\}} \left(\frac{var\_ncap_t}{d(t)} + ncap\_pasti_t\right) \\ & \times crf_s \times ncap\_cost_v \end{aligned} \tag{3.2}$$

Useful range for y: $\{m(t) - d(t) + 1, m(t) + elife_t - 1\}$

Case 1.b

$If\ ILED_t \ \leq ILED_{Min,t}$ and $TLIFE_t + ILED < D(t)$

$$\begin{aligned} invcost(y) = & \sum_{t \in milestone} indic(1.b) \\ & \times \sum_{v=\max\left\{B(t)-\left(\frac{tlife_t}{2}\right), y-elife_t+1\right\}}^{\min\left\{y, B(t)-\left(\frac{tlife_t}{2}\right)+c \times tlife_t - 1\right\}} \left(\frac{var\_ncap_t}{d(t)}\right) \times crf_s \\ & \times ncap\_cost_v \end{aligned} \tag{3.3}$$

Useful range for y: $\left\{B(t) - \left(\frac{tlife_t}{2}\right), B(t) - \left(\frac{tlife_t}{2}\right) + C \times tlife_t + elife_t - 2\right\}$

Case 2.a

$If\ ILED_t \ \geq ILED_{Min,t}$ and $TLIFE_t + ILED \geq D(t)$

$$invcost(y) = \sum_{t\in milestoneyears} indic(2.a)\times \sum_{k=\max\{B(t),y-elife_t+1\}}^{\min\{B(t)+ILED_T-1,Y\}} \left(\frac{var\_ncap_t}{d(t)}\right) \times crf_s\times ncap\_cost_{B(t)+\,ILED_t} \tag{3.4}$$

Useful range for y: $\{B(t), B(t)+ILED_t+elife_t-2\}$

Case 2.b

$If\ ILED_t\ > ILED_{Min,t}$ and $TLIFE_t+ILED<D(t)$

$$invcost(y) = \sum_{t\in milestoneyears, t\leq T(y)} indic(2.b)\times P_t(y) \tag{3.5}$$

Useful range for y: $\{B(t), B(t)+ILED_t+elife_t-2\}$

where

- $var\_ncap(t)$: Investment (new capacity) in a process.
- $ncap\_pasti(t)$: New capacity of past investments.
- $crf(s)$: capital recovery factor time slice s.

3.3.4. Decommissioning capital cost

Decommissioning happens when the technical life of the investment comes to an end. The dismantling capital costs have the same cases and rules that apply to investment costs. Original TIMES formulation differs decommissioning of the capital costs according to the above-mentioned cases four different decommissioning capital cost calculation options are defined.

In the TIMES modeling framework for large lump investments (investment on new nuclear power plant, new HTH facility for iron and steel production, etc.) and small investments (buying new refrigerator, air conditioning, etc.) have different decommissioning capital cost calculations with respect to the related streams of payments. For a generic representation, only the following formulation is presented in Equation 3.6.

$$decomcost(y) = \sum_{t \in milestones\ t \leq T(y)} indic \times \left(\frac{var_{ncap_t}}{tlife_t}\right) \times ncap\_dcost_{\ y-tlife_t} \times \begin{cases} 1\ if\ b(t) + \left\lceil \frac{tlife_t}{2} \right\rceil \leq y \leq b(t) + \left\lceil \frac{tlife_t}{2} \right\rceil + c.tlife_t - 1 \\ 0\ othewise \end{cases} \tag{3.6}$$

where

$$c = \langle \frac{d(t)}{tlife_t} \rangle$$

- $indic$: Indices that represent divisible projects, non-repetitive, progressive investment in period.
- var_{ncap_t}: Investment (new capacity) in a process on year t
- $tlife_t$: Technical lifetime of an investment of year t
- $ncap\_dcost_{y-tlife_t}$: decommissioning capital cost of a new investment with technical lifetime t on year y.

3.3.5. Fixed annual costs

The fixed annual costs those are modelled to be paid in the same year as the actual operation of the facility regardless of activity level, and it should be computed only for years “y” when the operation takes place for the process.

Considering the occurrence of annual fixed costs on year y; the payments appears to be the sum of all costs that belong to the investments made at periods before T(y), at T(y) itself, or at periods after T(y). Small projects (with a single investment/ repeated investment in a period), large indivisible projects (with unrepeated /repeated investments) have different fix cost formulations.

In this section only a representative formulation for fixed cost that belong to the investments that represent divisible projects, non-repetitive, progressive investment in period is given in Equation 3.7.

$$fixcost(y) = \sum_{t \in milestones \cup pastyears} indic \times \sum_{v=\max\{m(t)-d(t)+1, y-elife_t+1\}}^{\min\{m(t),y\}} \left(\frac{var_{ncap_t}}{d(t)} + ncap_{pasti_t}\right) \times ncap_{fom_v} \tag{3.7}$$

Useful range for y:

$$\{m(t) - d(t) + 1, m(t) + elife_t - 1\}$$

and $y \leq EOH$

where

- var_{ncap_t}: Investment (new capacity) in a process
- $ncap_{pasti_t}$: New capacity of past investments
- $ncap_{fom\_v}$: Fixed operating and maintenance cost of new investment for year v

3.3.6. Salvage value

Investments are assumed to release a lump sum revenue at the end of their useful lifetimes (if their technical lives end within the planning horizon). Another case is that if a technical life of an investment exceeds the planning horizon then the model adds the unused portion of the technical lives into the salvage value. In the TIMES modeling framework salvage value consists of three components; $salinv(eoh + 1)$, $salvdecom(eoh + 1)$, $salvsurv(eoh + 1)$ where eoh represents “the end of horizon”. The cases are that are constructed for investment costs are also valid for salvage value calculation. To cover the above mentioned cases four different salvage value calculation options are defined within the modelling structure. For a generic representation only the following formulation is given in Equation 3.8.

If the investment that has a technical life equals to TL is made in year k then related salvage value of an investment is calculated as follows;

$$S(k, TL) = \begin{cases} o\ if\ k + TL \leq EOH \\ 1\ if\ k > EOH \\ \dfrac{(1+d)^{TL-EOH-1+k} - 1}{(1+d)^{TL} - 1}\ otherwise \end{cases} \tag{3.8}$$

If an investment has a residual life time extending beyond the planning horizon, the investment costs includes the remaining decommissioning costs so to get this value as salvage cost provided in Equation 3.9 is utilized.

$$\begin{aligned} & salvdecom(eoh+1) \\ & = \sum_{t} indic \times \sum_{v=m(t)-d(t)+1}^{m(t)} \left(\frac{var\_ncap_t}{d(t)} + ncap\_pasti_t \right) \\ & \times ncap\_dcost_v \times sal(v, v + tlife_t) \end{aligned} \tag{3.9}$$

If an investment has a residual life time extends beyond the planning horizon, the salvaging of surveillance costs is calculated similar to salvdecom. The respective formulation is presented in Equation 3.10.

$$\begin{aligned} & salvsurv(eoh+1) \\ & = \sum_{t \in milestoneyears} indic(2.a) \times s(b(t) + iled_t + tlife_t \\ & \times var\_ncap_t \times ncap\_dlagc_{b(t)+iled_t} \\ & \times \sum_{l=b(t)+iled_t+tlife_t}^{same+dlag_t-1} disc(l, eoh+1) \end{aligned} \tag{3.10}$$

3.3.7. Supply Cost

This cost unit includes all expenses due to fuel consumption within the system. Unit supply cost is multiplied by the total fuel level supplied by a technology. If another input is needed to obtain a resource, it is investigated under “delivery cost” defined in the system.

$$
\begin{aligned}
&dannsupply(t) \\
&\qquad = \sum_{y=1}^{nyrsper} \frac{(1+discount)^{(1-y)}}{(1+discount)^{-startyrs+nyrsper*(t-1)}} \\
&\qquad * (\sum_{s-d} (scost(s,t) \\
&\qquad + \sum_{e} inpent(s_d, e, t) * delivent(s_d, e, t)) * r\_tsep(s,t) \\
&\qquad + \sum_{s\_nd} sign(s) * (scost(s,t) \\
&\qquad + \big(etranom(e,t) + edistom(e,t)\big) \\
&\qquad + \sum_{e} inpent(s,e,t) * delivent(s,e,t)) * r\_tsep(s,t) \\
&\qquad + \sum_{ce,w} (etranom(e,t) + edistom(e,t) \\
&\qquad + \sum_{e} inpent(ce,e,t) * delivent(ce,e,t)) * r\_tezy(ce,w,t) \\
&\qquad + \sum_{ch,z} (dtranom(e,t) \\
&\qquad + \sum_{e} inpent(ch,e,t) * delivent(ch,e,t)) * r\_thz(ch,z,t) \\
&\qquad + \sum_{ceh,w} (etranom(e,t) + edistom(e,t) + dtranom(e,t) \\
&\qquad + \sum_{e} inpent(ceh,e,t) * delivent(ceh,e,t)) \\
&\qquad * r\_tczyh(ceh,w,t))
\end{aligned}
\tag{3.11}
$$

where,

- $delivent(s,\ e,\ t)$: unit delivery cost of energy carrier e to technology s, at period t,
- $dtranom(e,\ t)$: unit transmission cost of energy carrier e (if the energy carrier e is LTH) at period t,
- $edistom(e,\ t)$: unit distribution cost of energy carrier e (if the energy carrier e is electricity) at period t,

- $etranom(e, t)$: unit transmission cost of energy carrier e (if the energy carrier e is electricity) at period t,
- $inpent(s, e, t)$: energy carrier e requirements of resource technology s at period t,
- $sign(s)$: sign parameter (which is -1 if the technology s is an export, +1 if the technology s is an import),
- $scost(s, t)$: unit supply cost of technology s at period t.

All calculations are done separately for domestic, import, and export resource sets. If the transmitted resources are not one of the standard energy carriers, but is electricity or LTH, then, the distribution and transmission costs over the system are also calculated under "supply cost" (In TIMES documentation, there are not detailed explanations, however it was mentioned that MARKAL calculations were unchanged. Variables of Equation 3.11 belong to MARKAL formulation).

3.3.8. Constraints

As mentioned before, the TIMES modeling framework has a bottom up structure based on optimization approach. In order to find the optimal value of objective function, numerous set of constraints must be satisfied. In TIMES modeling framework nine different constraint sets that express the relationships that provide a reliable structure for associate energy system is utilized. The sets are constructed as follows;

- Capacity Transfer
- Definition of process activity variables
- Use of capacity
- Commodity Balance Equation:
- Defining flow relationships in a process
- Limiting flow shares in flexible processes
- Peaking Reserve Constraint
- Constraints on commodities
- User Constraints

3.3.9. Capacity Transfer

Investing in a specific technology contributes to the total installed in that technology for the length of its physical life. Total capacity is linearly diminished due to wear and tear during overall lifetime.

Within the planning horizon for a specified time period t, total available capacity of each technology p is calculated by capacity transfer constraints. It considers all investments made before and on that period. Among them the one with a remaining technical life are added to the total capacity. The formulation that belong to capacity transfer constraint is presented in Equation 3.12.

$$capt(r,t,p) = \sum_{t-<life(r,t,p)} ncap(r,t',p) + resid(r,t',p) \tag{3.12}$$

where,

- $capt(r,t,p)$: total capacity of a technology p for region r in time period t.
- $life(r,t,p)$: technical lifetime of a technology p for region r in time period t.
- $ncap(r,t,p)$: new capacity installed of a technology p for region r in time period t.
- $resid(r,t,p)$: total residual capacity of a technology p for region r in time period t.

3.3.10. Definition of process activity variables

In the TIMES modeling framework two main group of variables are taken into consideration; technology related variables and commodity related variables. The flows of these two distinct components can be traced by introducing a constraint that equates an overall activity variable.

The modeler should set a single commodity to define activity level of a process. The commodity (if more than one commodity exists than the normalization should be done) can be selected from input or output set in order to determine the activity level of a considered technology.

$$act(r,v,t,p,s) = \sum_{c \in pcg} \frac{flow(r,v,t,p,c,s)}{actflo(r,v,p,c)} \tag{3.13}$$

where,

- $act(r,v,t,p,s)$: activity level of technology p with vintage year v for region r in time period t.
- $flow(r,v,t,p,c,s)$: flow level of a commodity c in technology p with vintage year v for region r in time period t.
- $actflo(r,v,t,p,s)$: activity conversion factor o of technology p with vintage year v for region r in time period t.

3.3.11. Use of capacity

The TIMES modeling framework not only make investment decisions but also adjust the capacity usage according to the maximum available capacity respective availability factor during certain time period (Keep in mind that the model have a choice to not use full-capacity of a technology). This constraint which is presented in Equation 3.14 assures that in a time period t for any technology p with a vintage year v cannot surpass its maximum available capacity level.

$$act(r,v,t,p,s) = af(r,v,t,p,s) * capunit(r,p) * fr(r,s) * cap(r,v,t,p) \tag{3.14}$$

where,

- $capunit(r,p)$: conversion factor between units of capacity and activity of a process p for region r.
- $fr(r,s)$: parameter is equal to the duration of time-slice s.
- $af(r,v,t,p,s)$: In region r, availability factor of technology p for time slice s in period t.

3.3.12. Commodity Balance Equation

In each region r, for any used commodity within a specific time period the value of domestic production and importation value should be equal to the summation of the amount that consumed within that region and exportation value. It is not sufficient to hold the commodity balance equation within a period, for all commodity types, they have to be satisfied in each time-slice. Although this type of constraint set is very complicated, to provide a brief overview a simplified version is given in Equation 3.15.

$$\begin{aligned}
&\Bigg[\sum_{p\in top_{(r,p,rout)}} flow(r,v,t,p,c,s) + sout(r,v,t,p,c,s) \times stg_{eff(r,v,p)} \\
&\qquad + \sum_{p,c\in prc_{ire(r,p,c,imp)}} trade(r,t,p,c,s,imp) \\
&\qquad + \sum_{p} release(r,t,p,c) * ncap(r,t,p,c)\Bigg] \\
&= \\
&\Bigg[\sum_{p\in top_{(r,p,r"in")}} flow(r,v,t,p,c,s) + sin(r,v,t,p,c,s) \\
&\qquad + \sum_{p,c\in prc\_ire(r,p,c,"exp")} trade(r,t,p,c,s,"exp") \\
&\qquad + \sum_{p} sink(r,t,p,c) * ncap(r,t,p,c) + fr(c,s) * dm(c,t)\Bigg]
\end{aligned} \tag{3.15}$$

where,

- $top(r,p,c,"in/out")$: an input/output flow of commodity c into/from process p in region r.
- $rpc\_ire(r,p,c,"imp/exp")$: an import/export flow into/from region r of commodity c via process p.
- $stg\_eff(r,v,p)$: the efficiency of storage process p.

- $com\_ie(r,t,c)$: the infrastructure efficiency of commodity c for time period t in region r.
- $release(r,t,p,c)$: the amount of commodity c recuperated per unit of capacity of process p dismantled for time period t in region r.
- $sink(r,t,p,c)$: the quantity of commodity c required per unit of new capacity of process p.
- $fr(s)$: the fraction of the year covered by time-slice s.

3.3.13. Defining flow relationships in a process

Some technologies require more than one types of commodities. If it is the case, it is necessary to define a relationship that control independent commodity flows within same technology by utilizing the formulation that is given in Equation 3.16. A constraint that controls the input output ratio under the condition of multiple inputs or multiple outputs must be included into the model.

$$\begin{aligned} &\sum_{c \epsilon cg2} flow(r,v,t,p,c,s) \\ &= flofunc(r,v,p,cg1,cg2,s) \\ &* \sum_{c \in cg1} coeff(r,v,cg1,c,cg2,s) * flow(r,v,t,p,c,s) \end{aligned} \tag{3.16}$$

where,

- $cg1$: input commodity group
- $cg2$: output commodity group
- $flofunc(r,v,cg1,cg2,s)$: efficiency ratio of technology p with vintage v in region r that consumes $cg1$ and produces $cg2$.

3.3.14. Limiting flow shares in flexible processes

For technologies require more than one types of commodities flow relationships are set by utilizing above mentioned constraint. Although it organizes a new efficiency formulation that allows production or consumption of multiple commodities, it cannot regulate the division of fuel shares. To put a restriction on this flexibility, lower and upper bounds can be defined into the model by employing the following constraint.

$$flow(c) \underset{\geq}{\overset{\leq}{=}} flowshare(c)\times \sum_{c\in cg} flow(c') \tag{3.17}$$

3.3.15. Peaking Reserve Constraint

The demand can vary not only within a time period but also time-slices. This type of constraint imposes a lower bound on all of the processes that produced a commodity for each time slice. The lower bound is set according to the commodity's average demand that belong to the peaking takes place e.g., summer time electricity demand for cooling, or winter night heating demand of natural gas.

$$\begin{aligned}\sum_{p\ producing\ c=cmg} & capunit(r,p)\times peak(r,v,p,c,s)\times fr(s)\times cap(r,v,t,p)\\ & \times actflo(r,v,p,c)\\ & + \sum_{p\ producing\ c=pcg} peak(r,v,p,c,s)\times flow(r,v,t,p,c,s)\\ & + trade(r,t,p,c,s,i)\\ & \geq [1+reserve(r,t,c,s)]\\ & \times\left[\sum_{p\ consuming\ c} flow(r,v,t,p,c,s) + trade(r,t,p,c,s,e)\right]\end{aligned} \tag{ 3.18}$$

where,

- e: the safety factor that required the installed capacity to be greater than the required capacity that can satisfy the largest demand for commodity c.
- $reserv(r,t,c,s)$: is the region-specific reserve coefficient for commodity c in time-slice s,
- $peak(r,v,p,c,s)$: the fraction of technology p's capacity in a region r for a period t and commodity c (electricity) that is allowed to contribute to the peak load in slice s.

3.3.16. Constraints on commodities

In the TIMES modeling framework, there exist an option to limit the usage rate and production amount of a commodity by simply setting bounds on a period. Cumulative bounds can also be imposed by this type of constraints that covers multiple periods, e.g., global bounds on total emission levels can be introduced by delimitating the supply amount.

4. ENERGY SECTOR STRUCTURE IN TURKEY

Over the last two centuries, industrialized societies have been demanding various kinds of energy and in increasing quantities. Recent technological innovations, increasing incomes, changes in the energy infrastructures and costs of fuels are the main reasons for these increases.

Energy is considered among the essential inputs for achieving economic and social development through the production process and services. This section aims to investigate the energy consumption of industries under the change of economic and social conditions throughout the years in Turkey.

Energy consumption in Turkey conjoint with population and industrialization entered a rapid increase phase especially after 1990. As the economic construct is structured based on exports, agriculture lost its importance, while industry and services sectors have come into prominence. As this shift in economic structure requires more energy, the demand for petroleum, natural gas, and coal type fossil fuels have increased. The demand changes in primary energy sources in Turkey from 1990 to 2012 is given in Figure 4.1.

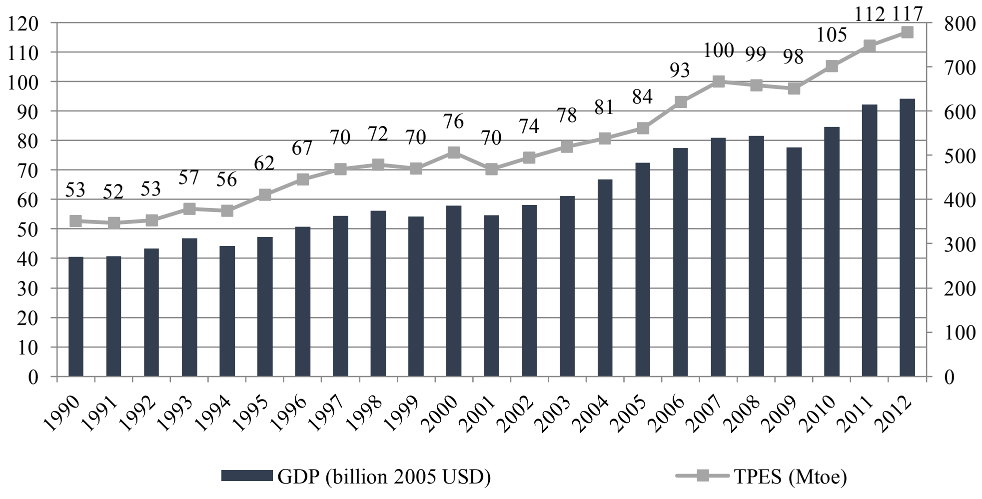


Figure 4.1. The change of primary energy consumption w.r.t. GDP.

Change in population is another major factor in energy consumption. According to Turkstat statistics population of Turkey was 56,5 million in 1990, while this number has almost reached 80 million. The energy consumption quadrupled from 50 TWh in 1990 to 207 TWh in 2012. Hence, the energy consumption per person increased from 909 kWh to 2760 kWh during the same period.

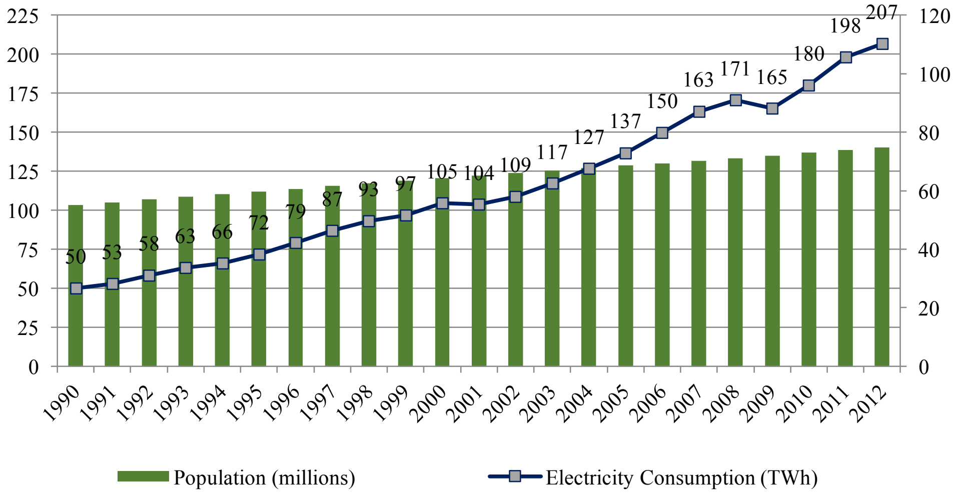


Figure 4.2. The change of electricity consumption w.r.t. GDP.

This increase in energy consumption undoubtedly resulted in an increase in CO_2 emissions. The relationship between fuel consumption and greenhouse gas emissions are given in Figure 4.2. A closer look at the numbers shows that the emission level in 1990 was 127 Mt CO_2, tripling to 302 Mt CO_2 in 2012.

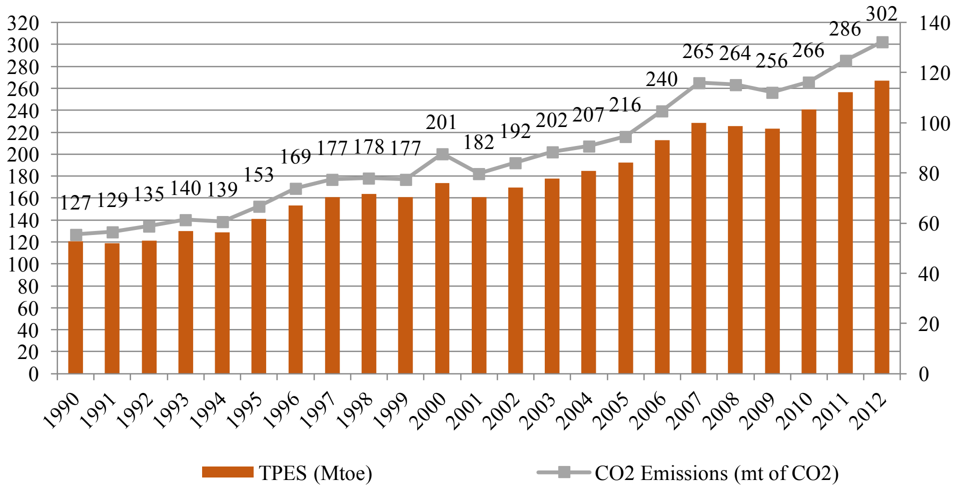
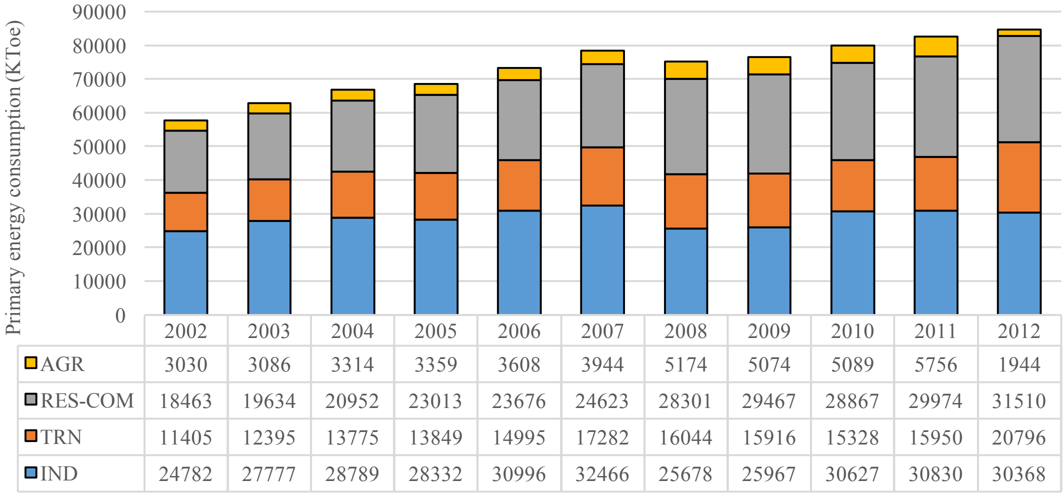


Figure 4.3. The change of CO_2 emissions w.r.t. primary energy consumption.

Energy service demands are the most significant player in the energy, economy, and environment modeling. To capture the characteristics of consumption, the general energy demand is clustered as aggregated demand sectors, namely; residential and service sector, industry sector, transport sector, agriculture sector, and power sector. Each of these five sectors is evaluated separately.

In the calibration phase, the demand for the power sector is adjusted in order to satisfy the energy demands of the above-mentioned five sectors. The primary energy consumption values of four primary consumption sectors, obtained from the general balance tables of last ten years announced by the Ministry of Energy, are given in Figure 4.4.



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
🟨AGR	3030	3086	3314	3359	3608	3944	5174	5074	5089	5756	1944
▨RES-COM	18463	19634	20952	23013	23676	24623	28301	29467	28867	29974	31510
🟧TRN	11405	12395	13775	13849	14995	17282	16044	15916	15328	15950	20796
🟦IND	24782	27777	28789	28332	30996	32466	25678	25967	30627	30830	30368

Figure 4.4. Breakdown of the primary energy resource consumption.

In Figure 4.4, only end-use energy demand sectors are given, and it shows how the distribution of demand among these sectors have shifted between years 2002 and 2012. When the demand distributions are investigated, it can be observed that demand of agriculture sector decreased from 5% in 2002 to 2% in 2012. Another interesting finding is the increase of transportation sector from 20% to 25%. When we look at the change in the industry sector, we also see a decrease in share due to the increases in residential, commercial, and transportation sectors. Although the energy demand of industry increased from its value of 24782 ktoe in 2002 to 30368 ktoe, the share in total decreased from 43% to 36%.

The current status in Turkey regarding these sectors, the foresight on how the demand will shape throughout the projection period, and basic information on sector-specific technologies and commodities are explained in the following section.

4.1. Sectoral Structure of Residential and Commercial Sector in Turkey

The residential and commercial sector is one of the biggest stakeholders among end-use demands with a 37% share. Exponential increase in urbanization and usage of household electronic devices will ensure that these industries will continue to demand a significant level of energy.

Buildings are products with long lifespans that consume high levels of energy. They encompass a wide range of products and services. Therefore, increasing energy efficiency in buildings is considered as a prioritized working area in climate change related policies and programs. EU and developed countries have always put actions that increase energy efficiency in buildings on top of their actions list for fighting against climate change.

The construct of the model for residential and commercial sector is constituted according to the EPA database. All the alternative technology options that provided by EPA are included into the model.

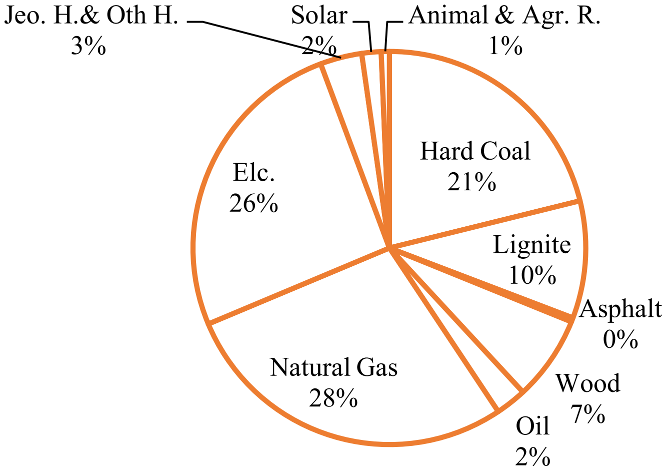


Figure 4.5. Energy consumption in the buildings w.r.t. to the energy types.

The EPA database is used to provide data to the model, and all alternative technologies that are planned to be activated before 2052 related to residential and commercial industry are included in the model. To understand the construct within the model for the energy usage that belong to residential and commercial sector in 2012, energy consumptions are presented in Figure 4.5. In residential and commercial sector, the demand increased almost 6000 ktoe to 31510 ktoe in 2012 from 2002. The highest share in consumed fuel is electricity and natural gas. Natural gas consumption share was 18% of total consumption in 2002, while it reached 28% in 2012. The main factors of this increase are the urbanization rate and infrastructure developments in the natural gas distribution network.

In 2012, 35.4% (31.5 million Toe) of total energy consumption was attributable to the residential and commercial sector. Although the demand for wood used as fuel has decreased, consumption of coal derivate has increased. In 2012 it reached 12216 ktoe which is almost 40% of the total demand. Although the efficiency of the indoor electronic devices has increased, changes in usage habits and the increase in the total number of devices used indoors resulted in a continually growing electricity demand which reached 8000 ktoe in 2012. Other energy sources used by residential and commercial sector for the base year are also given in Figure 4.6.

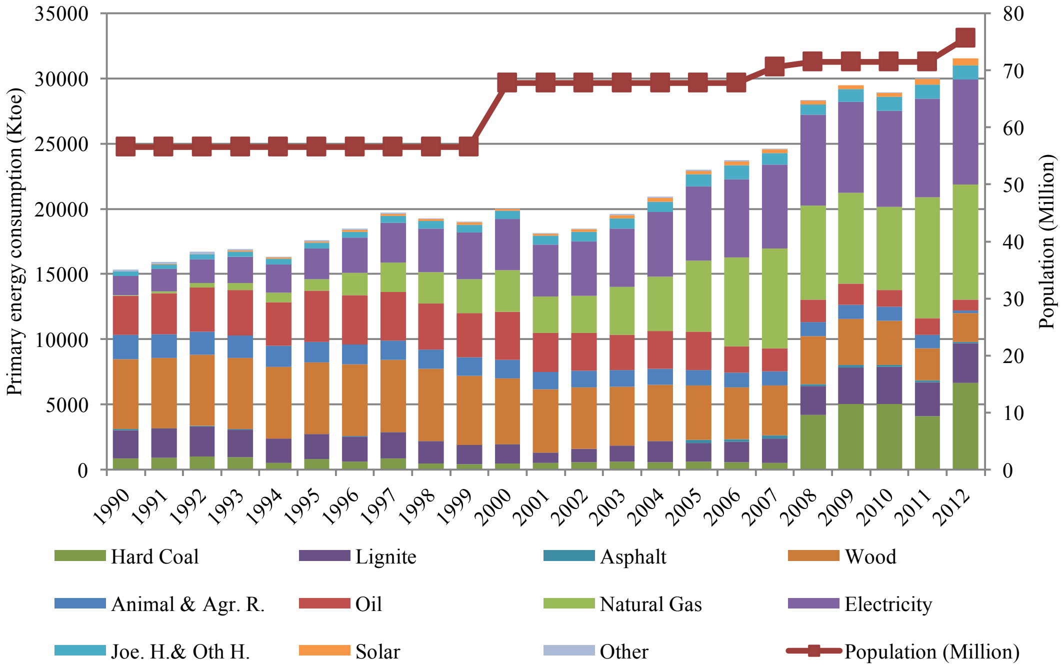


Figure 4.6. Energy consumption in the buildings.

As can be seen from the Figure 4.6 there is a relationship between the energy consumption pattern (that belong to the commercial and residential sector) and population. To project the future energy consumption of buildings, the data that presented in the “Building Census 2000” (TurkStat, 2001) is used and projected according to the population growth projection for the period of 2012-2050 (TurkStat, 2013).

The building age is distributed symmetrically with average equal to 50. Under the current assumption, the building stock and new buildings will have the following building lives: 5% 20 years, 15% 30 years, 20% 40 years, 30% 50 years, 20% 60 years, 10% 70 years, and 5% 80 years.

The number of stories is calculated under the assumption that an average number of stories is equal to 2.1 as presented in the same building census. For the remaining years up to base year (2012) Building Permit Statistics (TurkStat, 2013) is used to get the number of newly constructed buildings year by year. Additionally, number of new buildings constructed is calculated from the data according to the population projection. As mentioned before, the building stock projection is calculated by taking Turkish Statistical Institute population projection and average household size into consideration.

Table 4.1. Building classifications (TurkStat, 2001).

Building Classification	**Sub-Class**
Residential	(Residential + Mostly Residential)
Commercial Sector (Including Service sector)	Shop, store, mall and trade center etc., cinema, theatre etc.
	Education Buildings: Schools, private high schools, kindergartens
	Health Buildings: Buildings such as hospitals, maternity hospitals, sanatoriums etc.
	Sport: Sport centers such as sport halls (for indoor sports), gymnastic halls, skating rinks, target ranges etc.
	Transportation (train station, bus station, airport building etc.)
	Hotels: Buildings such as a hotel, a motel, a pension, a holiday village, an apart hotel etc.
	Administrative building: Buildings used to do all kinds of administrative and public services such as municipality buildings, post offices, public registration offices, administrative district, police stations.
	Religious: Buildings such as mosques, masjids, tombs, synagogues, patriarchates etc.

Average household size is predicted to drop to 3,3 in 2050 showing a linear decline (Hosgor and Tansel, 2010). Expected building stock is calculated from expected population ratio over average household size. When the numbers of buildings that are planned to be demolished are subtracted from the stock, numbers of new buildings are obtained. Expected numbers of buildings that are to be renewed are given in Table 4.2.

Table 4.2. Expected number of buildings to be renewed.

Construction period	**Number of Buildings**	**Expected number of buildings to be renewed**				
		2000-2009	**2010-2019**	**2020-2029**	**2030-2039**	**2040-2049**
Before 1929	327.575	327.575	0	0	0	0
1930-1939	186.079	124.053	62.026	0	0	0
1940-1949	346.112	197.779	98.889	49.445	0	0
1950-1959	700.290	323.211	215.474	107.737	53.868	0
1960-1969	1.376.482	323.878	485.817	323.878	161.939	80.970
1970-1979	3.047.300	320.768	641.537	962.305	641.537	320.768
1980-1989	4.673.253	233.663	467.325	934.651	1.401.976	934.651
1990-1999	5.804.126	0	290.206	580.413	1.160.825	1.741.238
Total		1.850.927	2.261.275	2.958.428	3.420.145	3.077.626

Table 4.3. Projection on number of dwellings and average number of households.

Year	**Population**	**Number of buildings**	**Ave. household**
2015	78.151.750	21.299.195	3,67
2020	82.076.788	22.685.930	3,62
2025	85.569.125	23.991.220	3,57
2030	88.427.604	25.154.279	3,52
2035	90.680.302	26.176.896	3,46
2040	92.257.821	27.032.407	3,41
2045	93.175.281	27.717.663	3,36
2050	93.475.575	28.237.710	3,31

Change in average building stock calculated from population increase and average household projection is shown in Table 4.3 and Figure 4.7. Energy demand is projected by taking the number of expected building demolitions/destructions and new building constructions into consideration to compensate the population increase.

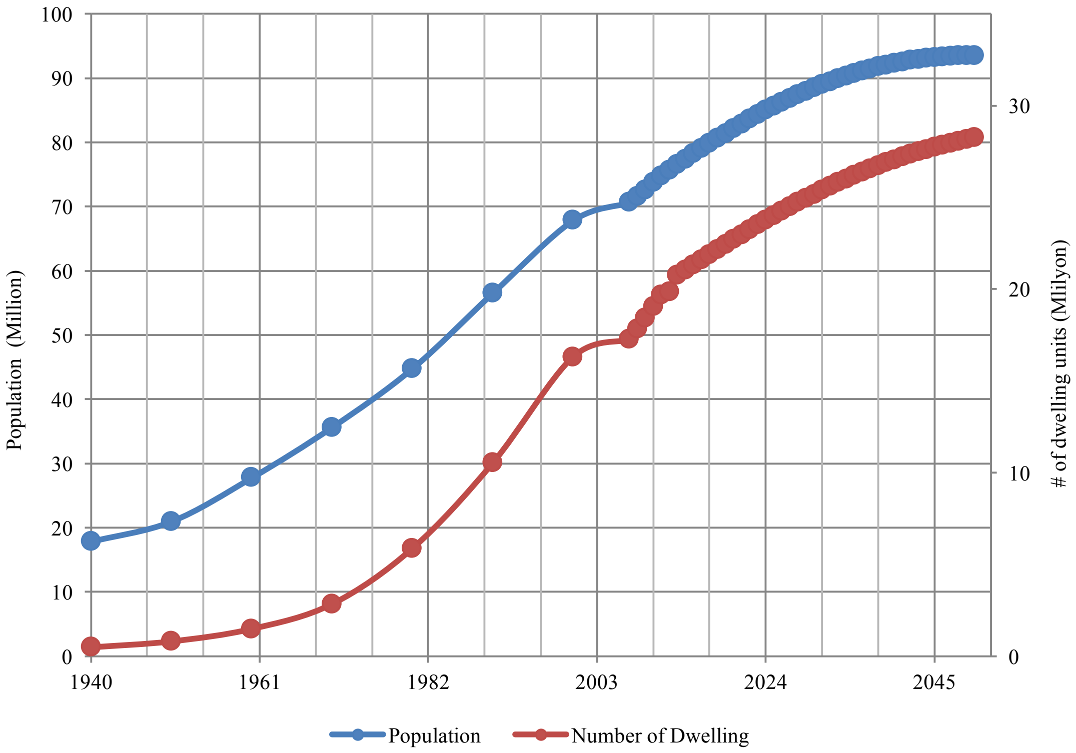


Figure 4.7. Dwelling stock change w.r.t. population growth.

4.1.1. Sectorial Commodities and Technologies

To cover all energy carriers that are taken into consideration in energy balance sheet, the following commodities given in Table 4.4 are defined in the model.

Table 4.4. Commodity definitions for the residential sector.

Nomenclature	**Description**
RSDELC	Electricity to Residential Sector
RSDGASNGA	Natural Gas to Residential Sector
RSDOILDSL	Diesel to Residential Sector
RSDOILLPG	LPG to Residential Sector
RSDAST	Asphaltite to Residential Sector
RSDCOAHRD	Hard Coal to Residential Sector
RSDCOALIG	Lignite to Residential Sector
RSDRNWBIO	Biomass-wood to Residential Sector after emissions
RSDRNWSOL	Solar Energy

The energy service demand technologies are set by the specified end-use demands. Energy efficiency is also modeled to capture the change in the performance of the technologies that are used. Additionally, capacity factor, lifetime, capital cost, operating and maintenance cost, input fuel type, hurdle rate and utilization factor parameters are added to specify each of the alternative technologies in the model.

The residential sector consists of demand technologies needed to meet residential demands for space heating and cooling, refrigeration, water heating, lighting, and other various energy uses as given in Table 4.5.

Annual and daily distributions are customized on demand type basis for each technology. For example, heating demand shows a Seasonal change, where for lighting demand a separation between day and night is done. In Table 4.5, sub-technology groups that feed the end user demands are formed.

For example, the demand technologies that serve to residential heating such as coal-fired boilers, natural-gas-fired boilers, electricity heating devices, heat pumps, etc. are used. For space cooling; room AC, central AC and heat pump technologies with the option to consume natural gas, LPG and solar are introduced into the model.

Existing stocks are first calculated at the national level using the data for energy consumption that belong to the respective energy technologies are calculated from the 2012 Energy Balance Table. In addition to this, the White Goods Manufacturers’ Association of Turkey (TurkBesd) main percent utilizations for each end use demand is gathered. For the case of lighting and durable goods stock, the average value that belongs to the survey conducted by TurkBesd is set as an existing stock (this data reveals the distribution of technology options w.r.t. the type of lighting as LED, Halogen, Linear Fluorescent, etc.).

As mentioned before, each sectorial technology is evaluated by the following elements; variable and investment costs, efficiency rate, capacity utilization factor, output generation level, and lifetime. For existing stock, the efficiency values are calculated and calibrated comparing to the fuel consumption values presented by the Ministry of Energy and Natural Resources.

All parameters of all mentioned technology and demand values are given in BUEMS_TR_CD.

Table 4.5. End-use demand technologies in residential sector

Nomenclature	**Description**	**Units**
RSH	Residential Heating	PJ/yr
RSC	Residential Cooling	PJ/yr
RWH	Residential Water Heating	PJ/yr
RRF	Residential Refrigeration	Million units/yr
RFZ	Residential Freezing	Million units/yr
RLT	Residential Lighting	PJ Lighting /yr
ROE	Residential Other Appliances - ELC	PJ/yr
ROG	Residential Other Appliances - NGA	PJ/yr
ROL	Residential Other Appliances - LPG	PJ/yr

Table 4.6. Existing technology stocks in residential and commercial sector (PJ)

Demand Description	**Fuel Type**	**TOTAL (TOE)**	**RSD**	**COM**	**EDU**	**CUL**	**OTH**
			93,4%	**4,3%**	**0,3%**	**0,01%**	**2,1%**
Heating	Hard Coal	6662	6221,6	283,8	17,3	0,7	137,9
	Lignite	3040	2839,1	129,5	7,9	0,3	62,9
	Asphalt	108	100,9	4,6	0,3	0,01	2,2
	Wood	2195	2049,9	93,5	5,7	0,2	45,4
	Other	211	197,1	8,9	0,6	0,02	4,4
	NGA (75%)	6625	6187,1	282,2	17,2	0,7	137,1
	ELC (11,3%)	913	852,7	38,9	2,4	0,09	18,9
Cooling	ELC (7.5%)	606	565,9	25,8	1,6	0,06	12,5
Water Heating	NGA (25%)	2208	2062,1	94,1	5,7	0,2	45,7
	ELC (7,2%)	582	543,5	24,8	1,5	0,06	12,1
Refrigeration	ELC (31,2%)	2520	2353,4	107,4	6,6	0,3	52,2
Freezing	ELC (7,2%)	582	543,5	24,8	1,5	0,06	12,1
Lighting	ELC (13,7%)	1105	1031,9	47,1	2,9	0,1	22,9
Other Appliances - ELC	ELC (6,7% +3,2% +8,5%)	1486	1387,8	63,3	3,9	0,2	30,8
Other Appliances - NGA	NGA	0	0	0	0	0	0
Other Appliances - LPG	Oil	804	750,9	34,3	2,1	0,08	16,6

The residential sector energy demand set is addressed in two categories of dwellings: existing houses (consists of energy consumption specifications for houses that built in the period of (1930 – 1980) (this division should be set), (2) new houses (as a representation of the building with isolation). The distribution of total consumption within commercial sectors and residential sector is done according to the existing number of buildings.

4.2. Sectoral Structure of Industry Sector in Turkey

To observe the changes in primary energy resources that the industry sector uses, the changes encompassing ten years before the base year 2012 are given in Figure 4.8.

Although a decrease is observed in years 2008 and 2009, there is an increase in energy consumption in this sector. The main reason for this intermittent decline is the global crisis in 2008. Mortgages and subprime loans triggered a financial crisis in us in the last quarter of 2007, which propagated to other industries. This created a domino effect disturbing all economies, turning the crisis into a global one, impacting Turkey as well.

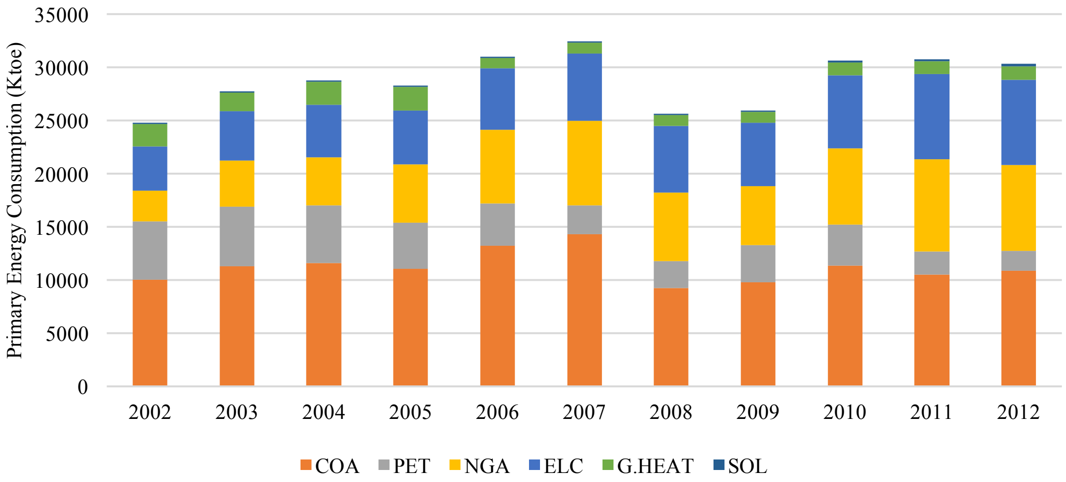


Figure 4.8. Breakdown of the primary energy consumption of industry sector.

When we explore the distribution of fuel types, it is observed that energy devoid is based heavily on coal, while the second source is natural gas. Coal consumption is around 40% levels. This number peaked at 44% in 2007.

Natural gas consumption inevitably increased. In 2002, 12% of all industry energy consumption was natural gas, in 2012 the share increased to 26%. The consumption value was 2902 ktoe in 2002, and 7173 ktoe in 2012.

Table 4.7. Energy demands w.r.t. technologies.

Sub-industry	**Year**	**Heat power for main processes**	**Steam power**	**Engine power**	**Heat power for other processes**	**Other**	**Non-energy input**
3- Production	1999	72,3%	10,5%	11,4%	0,1%	5,7%	0,0%
	2000	71,0%	10,8%	10,8%	0,1%	7,2%	0,0%
	2001	70,6%	11,8%	10,2%	0,1%	7,4%	0,0%
31- Food, Drinks, and Tobacco	1999	72,9%	4,7%	10,7%	0,0%	11,8%	0,0%
	2000	66,4%	11,3%	10,2%	0,0%	12,2%	0,0%
	2001	66,3%	11,7%	10,7%	0,0%	11,2%	0,0%
32- Woven, Clothing, and Leather	1999	49,1%	9,8%	25,4%	0,1%	15,6%	0,0%
	2000	48,7%	10,8%	24,2%	0,1%	16,2%	0,0%
	2001	46,6%	13,7%	25,2%	0,3%	14,2%	0,0%
33- Forestry products, and Furniture	1999	31,5%	20,4%	27,4%	0,0%	20,7%	0,0%
	2000	32,0%	31,7%	25,5%	0,0%	10,8%	0,0%
	2001	33,8%	32,0%	26,2%	0,0%	8,0%	0,0%
34- Paper, paper products and printing	1999	56,8%	16,3%	14,6%	0,2%	12,2%	0,0%
	2000	56,0%	17,2%	15,4%	0,1%	11,3%	0,0%
	2001	54,2%	20,7%	13,5%	0,2%	11,5%	0,0%
35- Chemical-Petroleum, rubber and plastic products	1999	72,7%	16,3%	7,0%	0,4%	3,5%	0,0%
	2000	69,5%	15,3%	7,0%	0,3%	7,8%	0,0%
	2001	70,1%	15,0%	6,5%	0,0%	8,3%	0,0%
36- Stone and stone based products	1999	84,4%	1,5%	10,8%	0,0%	3,3%	0,0%
	2000	82,9%	2,7%	10,3%	0,0%	4,0%	0,0%
	2001	84,7%	2,3%	10,2%	0,0%	2,8%	0,0%
37- Metal	1999	44,3%	11,7%	10,9%	0,0%	4,0%	29,0%
	2000	45,5%	11,1%	9,8%	0,0%	5,0%	28,4%
	2001	43,3%	13,3%	8,4%	0,0%	6,3%	28,6%
38- Metal products, machinery, equipment, transport equipment, scientific measuring tools	1999	33,4%	5,1%	33,7%	0,1%	27,8%	0,0%
	2000	28,8%	10,6%	32,8%	0,6%	27,1%	0,0%
	2001	27,7%	12,6%	32,7%	1,8%	25,2%	0,0%

Demand for electricity has also increased in recent years. In 2012, a total of 93,175 GWh of electricity was consumed by the industry sector. This consumption corresponds to 26% of total energy demand. Energy consumptions are correlated to Sectoral production by calculating energy demand per ton.

Production amounts on industries are determined from the data collected from open source data screening. For industries that production figures cannot be given in tons, production values are tracked on the monetary base.

As long-term production industry projections and percentage changes of sub-industries cannot be obtained, the percentage distributions of sub-sectors are assumed to be constant for the projection period. For GDP, the World Bank forecast is taken into account and growth rate of industries are assumed to be directly proportional to the GDP (except for Iron-Steel, Clinker and Ceramics industries).

To generate industry specific energy breakdowns, "Energy Consumption of Production Industry (Companies that consume 500 ton or more equivalent petrol)" report published by Turkish Statistical Institute in 2004, is used. In the report, for nine main industries energy consumption is given with respect to fuel type and areas of usage. To make the data compatible with the model, steam consumption is added to steam power usage, electric consumption is added to engine power usage, and other fuels are added to heat power usage.

Similarly, steam consumption given under heating topic is added to heating power for other processes. Fuel consumption under electricity is added to steam power usage. Also, the metal industry where non-energy raw material input usage is significant, the coke consumption is given under production, is added to the raw material input.

On the other hand, the data for the chemical industry is not detailed and consequently omitted. In other industries, the non-energy raw material input is also not taken into consideration. For 1999, 2000, and 2001, the calculated energy demand ratios are given in Table 4.7.

4.2.1. Sectorial Commodities and Technologies

The industry sector energy demand set is divided into 11 industrial sub-sectors as given in Table 4.8. The final energy demands that belong to each sector that prepared according to the EPA classification are given in Table 4.8.

Table 4.8. Abbreviations that belong to industrial sectors.

Demand Sectors	**Units**	**Description**
ICOA	PJ/yr	Chemicals and Fertilizer Industry
ICR	PJ/yr	Ceramic Industry
IFD	PJ/yr	Food Industry
IMAE	PJ/yr	Primary Aluminum Industry
IMO	PJ/yr	Other Metals
IMS	PJ/yr	Steel Industry
IMT	PJ/yr	Secondary Steel Industry
INC	PJ/yr	Cement Industry
ING	PJ/yr	Glass and Non-Metal Minerals Industry
IOT	PJ/yr	Other Industry
IPL	PJ/yr	Pulp and Paper Industry

To meet the six different demands belonging to the defined industry types in Table 4.9, the following commodities are defined in the model as given in Table 4.10.

Table 4.9. Energy carriers to end-use demand technologies.

Sector	**Technology**	**Description**
ICOA, ICR, IFD, IMAE, IMO, IMS, IMT, IM, INC, ING, IOT, IPL	STM	Steam
	PRH	Process Heat
	MDR	Machine Drives
	FAC	Facility
	FEED	Feedstock
	HEAT	Other Heat

Table 4.10. Commodity definitions that defined in the industry sector.

Nomenclature	**Description**	**Nomenclature**	**Description**
INDELC	Electricity to Industry Sector	INDOILLPG	LPG to Industry Sector
INDGASNGA	Natural Gas to Industry Sector	INDAST	Asphaltite to Industry Sector
INDCOKE	Coke to Industry Sector	INDCOAHRD	Hard Coal to Industry Sector
INDPTC	Petro-coke to Industry Sector	INDCOALIG	Lignite to Industry Sector
INDGSL	Gasoline to Industry Sector	INDRNWBIO	Biomass to Industry Sector
INDOILDSL	Diesel to Industry Sector	INDRNWSOL	Solar Energy to Industry Sector
INDKER	Kerosene to Industry Sector		

4.3. Sectoral Structure of Transport Sector in Turkey

As mentioned before, the transport sector is presented into the model with respect to the mode of transport. To represent the current status of the transport type general information is given respectively. In this study, the air transport is considered just for domestic flights, (international flights being excluded). According to the air traffic information gathered from the Republic of Turkey General Directorate of State Airports Authority, total domestic passenger and Cargo traffic data is included into the model. For base year consumptions the data provided by The Ministry of Energy and Natural Resources is used.

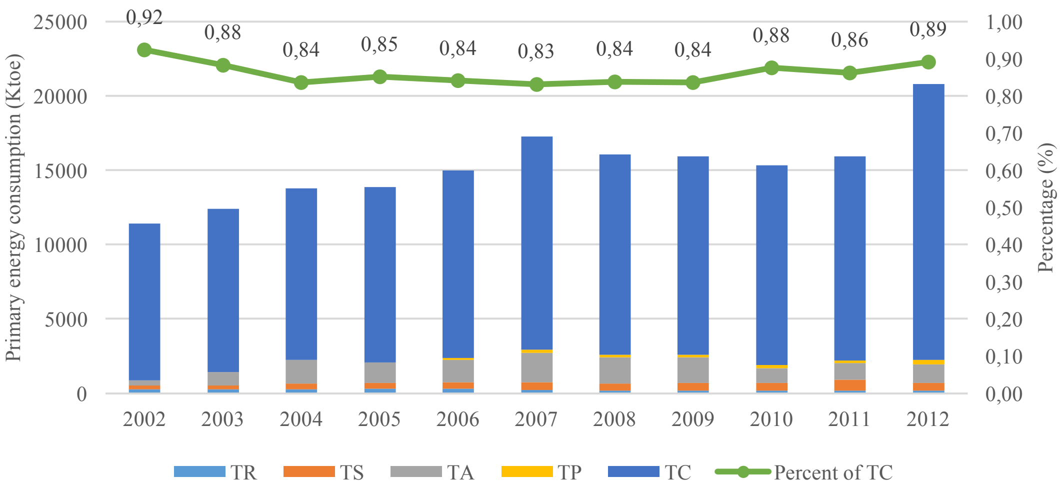


Figure 4.9. Breakdown of the primary energy consumption of transport sector.

For rail transport, data regarding railroads are obtained from Ministry of Transport, Maritime Affairs, and Communication (UDHB), and Turkish Statistical Institute. Existing efficiency values are calculated by comparing the current mileage values and total energy consumptions that belong to the base year.

For road transport, to track average annual vehicle-kilometers (vkm) the road transport main classifications that represented in the EPAUS9r model is used. The data that belong to the road transport is gathered from Ministry of Environment and Urbanization and projected to 2052 under the assumption that transport demand has a linear relationship with the GDP level. First, the vehicle stocks in fuel type are calculated then for each time approximate distance traveled is gathered. Existing technology stock that belongs to road transport is given in Vehicles (Million) in given in Table 4.11.

Table 4.11. Existing car storage that belong to each car type.

	Fuel Type	**Vehicles (Million)**
Passenger Cars	PET	6338881
Passenger Cars	DIE	2088685
Light Duty Vehicles	PET	1918132
Light Duty Vehicles	DIE	1173093
Heavy Goods Vehicles Rigid	DIE	383718
Heavy Goods Vehicles Artic	DIE	363180

Regarding maritime transport, just domestic operations are considered under six sub-modes, which are dry cargo ships, bulk carriers, container ships, tankers, urban passenger boats and intercity ferry-boats. Since the data acquired from Republic of Turkey Ministry of Transport, General Directorate of Maritime Affairs and Inland Waterways Organization is not sufficient enough to cover all of the detailed information, for the base year, only general fuel consumptions are taken into account to find the existing efficiency values.

4.3.1. Sectorial Commodities and Technologies

The transport sector energy demand set is addressed regarding transportation modes (such as air, road, rail, and sea). Then, for each transportation mode, vehicle types serving or having the potential to serve are defined and classified. Also, for each vehicle type, several technologies based on available and potential future fuels are defined. The model data regarding these sub-modes are compiled from various state institutions, private companies, governmental and non-governmental organizations.

Table 4.12. Commodity definitions that are used in the transport sector.

Nomenclature	**Description**
TRNELC	Electricity to Transport Sector
TRNGASNGA	Natural Gas to Transport Sector
TRNOILDSL	Diesel to Transport Sector

Table 4.12. Commodity definitions that are used in the transport sector (cont.)

Nomenclature	**Description**
TRNOILLPG	LPG to Transport Sector
TRNGASLNG	LNG to Transport Sector
TRNGASCNG	Compressed Natural Gas to Transport Sector
TRNOILGSL	Gasoline to Transport Sector
TRNOILJTF	Jet fuel to Transport Sector
TRNOILRFL	Residual Fuel Oil to Transport Sector
TRNRNWBDL	Biodiesel to Transport Sector
TRNRNWETH	Ethanol to Transport Sector

Technologies that belong to the transportation sector are considered separately for each transportation mode. Basic abbreviations, alternative fuel types and units are given in Table 4.13.

Table 4.13. End-use demand technologies in transport sector.

Nomenclature	**Fuel Type**	**Description**	**Units**
TA	Jet fuel, gasoline	Domestic Air Transport	PJ
TB	Gasoline, diesel, biodiesel, CNG, LPG, Hydrogen, Fuel cell	Bus	Bn-vkm (Billion vehicle km travelled)
TC	Gasoline, diesel, biodiesel, CNG, LPG, Hydrogen, Fuel cell	Commercial Trucks	Bn-vkm (Billion vehicle km travelled)
TRF	Diesel, electricity	Freight Rail	PJ
TRP	Diesel, electricity	Freight Passenger	PJ
TS	Residual oil, diesel	Shipping	PJ

4.4. Sectoral Structure of Agriculture in Turkey

In the first years of the Republic, the share of agriculture in national economy was around 40%. This share in GDP have constantly declined throughout years; 36% in 1970, 25% in 1980, 16% in 1990, and 13.5% in 2000. However, the share of agriculture is still at a very high level when compared with other developed countries (DBT, 2014).

Energy consumption values in agriculture was 1956 ktoe in 1990, then increased to 2556 ktoe in 1995, 2964 ktoe in 2001. Although the energy consumption in agriculture constantly increases, the share of energy consumption does not show a similar trend. Share of energy consumption of agriculture was 5.3% in 2002, then it declined to 5% in 2007. In 2012, the general balance calculations have changed so that diesel fuel consumption of tractors that were previously calculated within agriculture have been transferred to transportation. Hence, the share of agriculture dropped to 2.3%.

When energy consumption is investigated on fuel type base; directly consumed energies are electricity, coal, petroleum products, and natural gas. Energy is consumed during production, repair and maintenance of various agricultural tool or machines. The direct and indirect energy consumption are taken into consideration, composing the total energy costs.

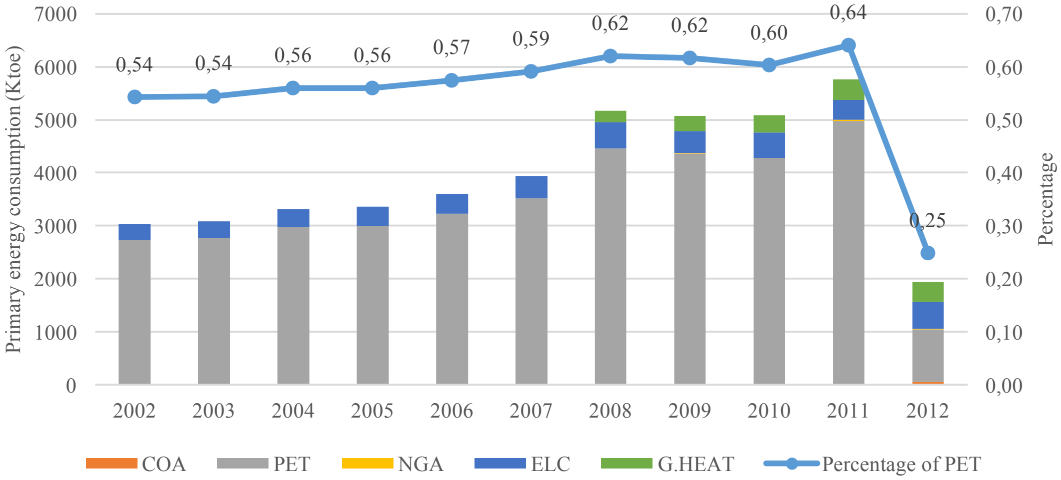


Figure 4.10. Breakdown of the primary energy consumption of agriculture sector.

4.4.1. Sectorial Commodities and Technologies

The agricultural sector demand set is based on the energy type demanded by agricultural activities, the primary types being natural gas, coal, diesel, and electricity. No sub-sectors are defined for this sector. The representative end use demands are given in Table 4.14.

Table 4.14. End-use demand technologies in agriculture sector.

Nomenclature	Description	Units
AGRCOAHRD	Hard Coal to Agriculture Sector	PJ
AGRELC	Hard Coal to Agriculture Sector	PJ
AGRGASNGA	Natural Gas to Agriculture Sector	PJ
AGROILDSL	Diesel to Agriculture Sector	PJ
AGROILRFO	Residual Fuel Oil to Agriculture Sector	PJ
AGRRNWGEO	Geothermal Power to Agriculture Sector	PJ

4.5. Sectoral Structure of Power Sector in Turkey

As an infrastructure sector, the power sector provides direct or indirect input to all sectors. In this aspect, any value added from a sector, power sector has a share. Thus, this sector is has a significant importance.

Over the course of the years, the Turkish power market has been developing in accordance with monetary improvements driven by industrialization and growth in population followed by increased level of urbanization.

When Republic of Turkey was founded in 1923, the total installed power was 33 MW. This number have increased 1729 times in 89 years, reaching 57059 MW in 2012 in order to meet the increasing demand (EMO, 2006; TETC, 2013). In 2012, approximately 242 TWh of electricity was produced to meet the domestic market needs (Deloitte, 2013). The change in installed power throughout years published by TETC is given in Table 4.15 (TETC, 2013).

The two main sources for electricity production are lignite and hydropower. In 1990, 30% of total installed power was lignite, while 40% was hydropower. Same year, the total installed power was 16318 MW. When we reach 2000’s it is observed that investment in natural gas have increased. In 1990’s natural gas had an 11% share in total electricity production when it first entered the installed power, this share reached 18% in 2000’s with 10976.2 MW. In 2007, it peaked at 27% but then declined slightly to 25% in 2012 with 14116 MW.

Share of hard coal in 2005 was very low until 2005. In 2006, its share was 5% with 1986 MW of installed power reaching 4383 MW in 2012. The opposite is observed for lignite.

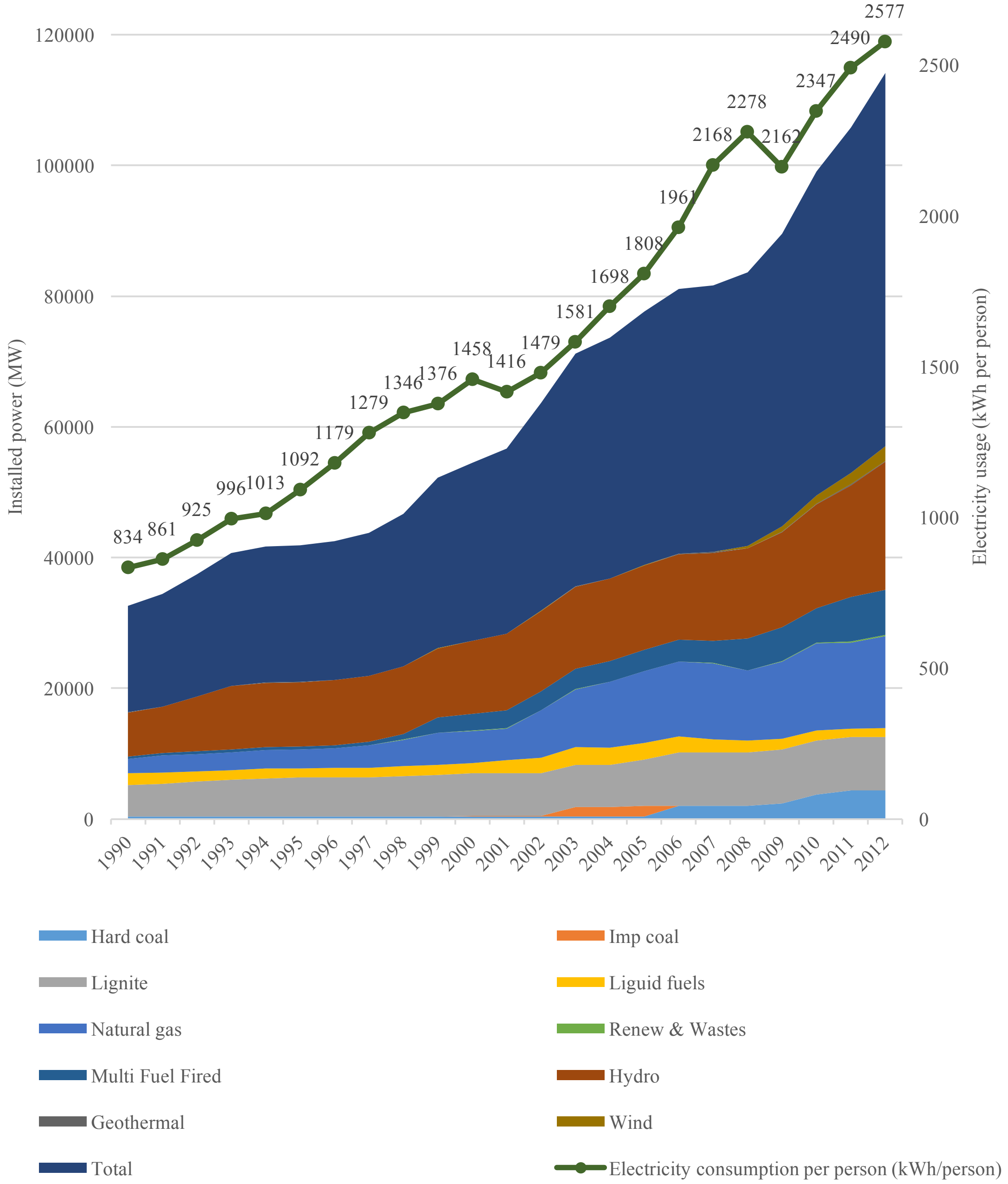


Figure 4.11. Annual development of Turkey's installed capacity.

In 1990's share of lignite was around 30%, which dropped to 18% in 2003, and to 14% in 2012. Although its share in total installed power declined, the total installed powered have doubled reaching 8193 MW.

When we look at the renewable energy sources, hydroelectric power got the lions share with 41%. This situation continued until 1997 and reached its maximum level of 47% with 10103 MW. Although the investments have brought total to 19609 MW in 2012, the share in total installed power have dropped to 34%.

Table 4.15. Local and renewable energy potentials (2012) (Source: MENR).

Resource type	**Installed capacity (MW)**	**Total potential capacity (MW)**	**Rate of utilization of potential (%)**	**Electricity generation (GWh)**
Hydro power	19.619	47.497	41,3	57.840
Wind	2.312	48.000	4,8	5.851
Solar	-	56.000	-	-
Geothermal	162	640	25,3	849
Biomass	158	2.000	7,9	659
Total	22.251	154.137	14,4	65.199
Lignite	8.148	20.000	40,7	34.397
Coal	335	500	67	1.733
Total	8.483	20.500	41,3	36.130
TOTAL	30.734	174.637	17,5	101.329

Wind energy, as another renewable source attracted investors after 2008, gaining importance afterwards. Before 2008, only 20 MW of installed power, increased 100 times to 2261 MW in just 4 years with the help of government incentives. A similar situation is observed for geothermal energy.

Until 2005, maximum installed power for geothermal energy was 18 MW, reaching 162 MW in 2012. Figure 4.11 gives how installed power is formed throughout years including the distribution based on fuel types. When the base year is investigated, the hydropower leads with 35% share, followed by natural gas with 25%.

The most important potential for renewable energy sources in Turkey is hydropower. Gross hydroelectric potential is 433 billion kWh/year, technical potential is 216 billion kWh/year, and economic potential is 164 billion kWh/year (GDSHW, 2013).

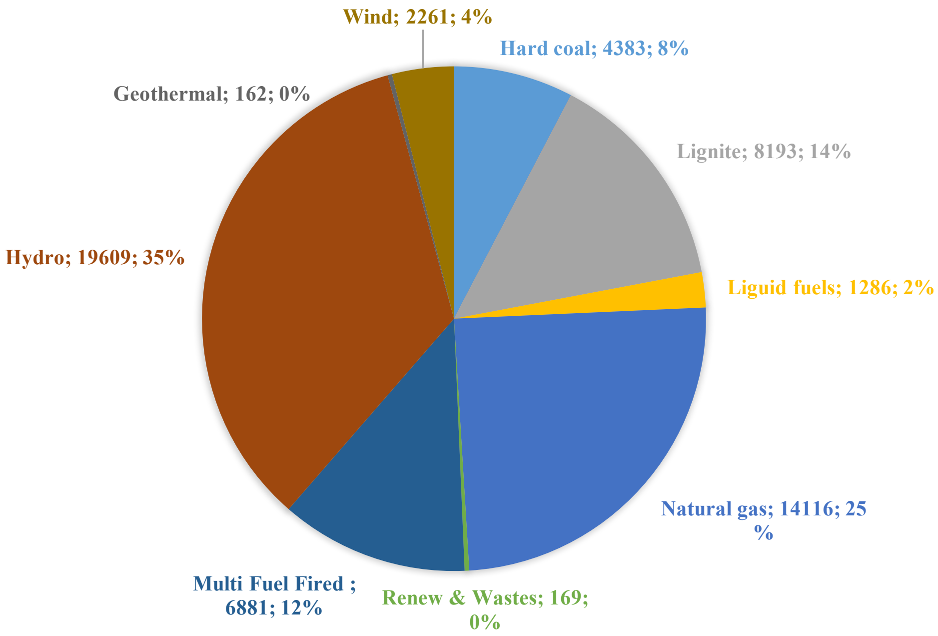


Figure 4.12. Electricity generation and shares by energy resources in 2012 (MW).

Turkey has 1% of world's total theoretical, and 16% of Europe's total economic hydroelectric potential. However, Turkey is not utilizing the renewable energy potential. Only 41.3% of hydroelectric potential, 4.8% of wind potential, 25.3% of geothermal potential, and 7.9% of biomass potential is utilized. The installed power equivalence of total renewable sources potential is 154137 MW. Turkey is using only 12.9% to produce electricity. Capacity usage rates are given in Table 4.15.

Another important resource is lignite with 8193 MW installed power. When lignite and hard coal mined in Turkey is added to this value, the power potential increases to 174637 MW. These numbers are more than triple the current installed power. So, if these resources are utilized efficiently there should be no dependency to other countries for electricity supply. With changing life conditions, and industrialization, the demand per person increased from 834 kWh in 1990, to 2577 kWh in 2012. When increasing urbanization rate, and population, an increase in electricity demand is inevitable.

To increase supplier capacity, reduce dependency on a single source, investment to different sources should be increased. This will increase energy security and decrease dependency to other countries. The foresights regarding the demand at the end of modeling period, and how the resource investments shape will be given in the results section.

4.5.1. Sectorial Commodities and Technologies

The Power sector consists of conversion technologies that take in fuel resources and convert them into electricity for use in the end-use sectors. Power plant capacity is modeled as gigawatts (GW), and power plant costs are given in terms of dollars per GW.

Table 4.16. Commodity definitions that defined in the transport sector.

Nomenclature	**Description**	**Nomenclature**	**Description**
PWRCOACOKE	Coke to Power Sector	PWROILASP	Asphaltite to Power Sector
PWRCOAHRD	Hard Coal to Power Sector	PWROILDSL	Diesel to Power Sector
PWRCOALIG	Lignite to Power Sector	PWROILRFO	Residual Fuel Oil to Power Sector
PWRGASNGA	Natural Gas to Power Sector	PWRRNWBIO	Biodiesel to Power Sector
PWRNUKURN	Uranium to Power Sector	PWRRNWHYD	Hydro to Power Sector
PWRNWGEO	Geothermal to Power Sector	PWRRNWSOL	Solar to Power Sector
PWRNWMSW	Waste to Power Sector	PWRRNWWND	Wind to Power Sector

As electricity is produced, the output is converted to PJ of electricity through a conversion factor of 31.536 PJ/GW. The technologies represented range from fossil fuel conversion technologies to nuclear and renewable technologies.

Table 4.17. Power sector existing technologies.

Technology	**Description**	**Technology**	**Description**
EBIOSTMR	Wood/Biomass Steam	ENGACCRO	Natural Gas Combined-Cycle; Open Loop Cooling
EDSLCCR	Diesel Oil Combined-Cycle	ENGACCRR	Natural Gas Combined-Cycle; Recirculating Cooling
EDSLCTR	Diesel Oil Combustion Turbine	ENGACTR	Natural Gas Combustion Turbine
EHYDCONR	Hydroelectric, Conventional	ENGASTMRO	Natural Gas Steam; Open Loop Cooling
EHYDREVR	Hydroelectric, Reversible	ENGASTMRR	Natural Gas Steam; Recirculating Cooling
ELFGGTRR	Landfill gas to energy: Gas Turbines	ERFLSTMR	Oil Steam (Resid Fuel Oil LS)
ELFGICER	Landfill gas to energy: Engines	ESOLPVR	Solar Photovoltaic

Table 4.17. Power sector existing technologies (cont.)

Technology	**Description**	**Technology**	**Description**
ELFGSTRR	Landfill gas to energy: Steam Turbines	EURNALWRO	Pre-Existing Nuclear LWRs; Open Loop Cooling
EMSWSTMR	Municipal Solid Waste Steam	EURNALWRR	Pre-Existing Nuclear LWRs; Recirculating Cooling
ENGACCRD	Natural Gas Combined-Cycle; Dry Cooling	EWNDR	Wind

The existing technologies are characterized by residual capacity (RESID), fixed Operating and M (FIXOM), variable Operating and M (VAROM), plant lifetime (LIFE), availability (AF or AF(Z)(Y)), and efficiency (INP(ENT)c).

Table 4.18. Power sector future technologies.

Technology	**Description**	**Technology**	**Description**
EBIOIGCC	Biomass Integrated Gasification Combined-Cycle	ENGACCCCS	Natural Gas Combined Cycle -- CO_2 Capture
ECOALIGCC	Integrated Coal Gasif. Combined Cycle	ENGACT05	Natural Gas Combustion Turbine
ECOALIGCCS	Integrated Coal Gasif. Combined Cycle -- CO_2 Capt.	ESOLPVCEN	Solar PV Centralized Generation
ECOALSTM	Pulverized Coal Steam - 2010	ESOLSTCEN	Solar Thermal Centralized
EGEOBCFS	Geothermal - Binary Cycle and Flashed Steam	ESOLPVCOM	Solar PV Distributed Commercial
EGEOR	Geothermal, Residual	ESOLPVRES	Solar PV Distributed Residential
ELFGGTR	Landfill gas to energy: Gas Turbines	EURNALWR15	Nuclear LWRs, Available in 2015
ENGACC05	Natural Gas - Combined-Cycle Turbine	EWNDCL4A	Wind Generation Class 4 Cost Category A
ENGAACC	Natural Gas - Advanced Combined-Cycle Turbine	EWNDCL4B	Wind Generation Class 4 Cost Category B
ENGAACT	Natural Gas - Advanced Combustion Turbine	EWNDCL4C	Wind Generation Class 4 Cost Category C

In production of electrical energy as a secondary energy source that is obtained from a series of processes applied to primary energy sources; unrenewable sources such as petroleum, natural gas, coal derivatives (lignite, coke, etc.), nuclear energy, renewable sources such as hydroelectric and biomass, and natural energy sources such as sun, wind, and geothermal are used. In this section, information about the reserve statuses of the resources that will be used by the before-mentioned sectors will be provided.

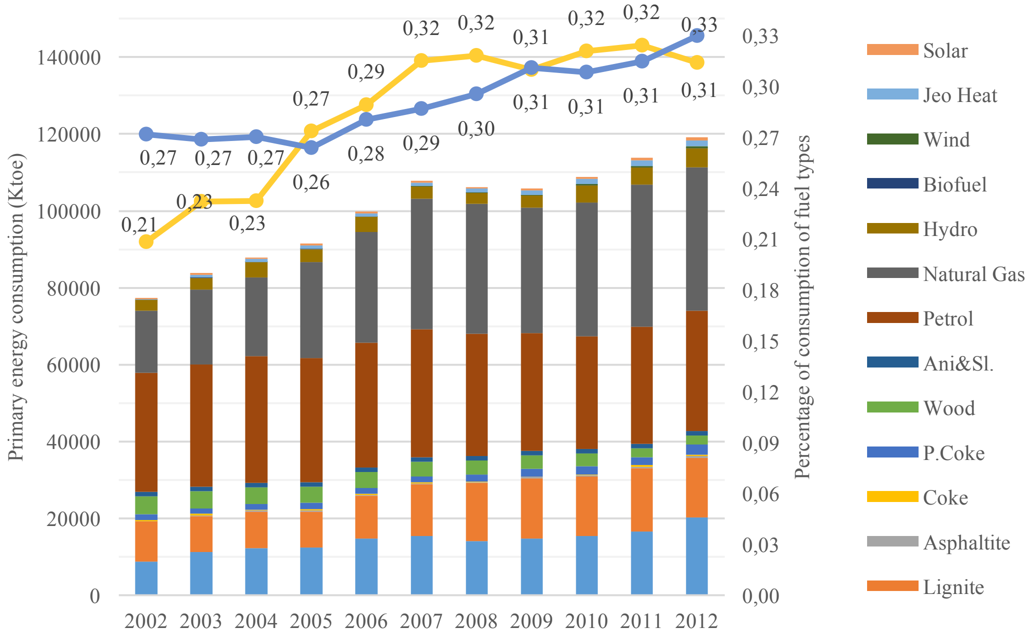


Figure 4.13. Primary energy consumptions by fuel type.

First, when we look at the distributions of sources, in 2012, coal takes the first places with 32.7% in energy supply, followed by natural gas with 31.1%, and petroleum with 26.0%, remaining 10.2% is supplied by renewable sources and others.

If we take a closer look at the natural gas consumption, it is observed that in 2012 50.8% of the total natural gas sold in Turkey was used for electricity production (48.1% in 2011), 23.8% was used for households (25.8% in 2011), 23.9% in industry (24.2% in 2011) (EGC, 2013).

When change in coal consumption throughout the years is investigated, it is observed that it is the most favorite fuel type of Turkish energy sector, while natural gas is a close second. In 2007, 33953 ktoe of natural gas consumption had a share of 32% in total energy consumption. In the last decade Turkey leads in Europe with respect to increases in electric and natural gas demands (EGC, 2013).

Petroleum consumption was 30890 ktoe in 2002. This number reached 33896 ktoe in this 10-year period. A significant increase is observed in usage of renewable sources. In 2002, the wind demand was 4 ktoe, which increased 162 times reaching 650 ktoe. According to Turkish Wind Power Statistics Report a 500 MW wind energy investment is made annually by 2009.

Similarly, the geothermal power demand increased from 90 ktoe to 1463 ktoe. Although it lags behind other types of renewable resources, solar power demand has doubled to 795 ktoe in 2012. Turkey is in the solar band zone and have an important potential in this area.

For fossil energy resources, Turkey is a net importer with 92% of petroleum, 99% of natural gas, 95% of mineral coal is being imported. This brings the total to 73.4% of energy demand being met by import. The leading reasons why we are an importer is the small share of fossil fuel potential in Turkey. While Middle East and Caucasia have rich petroleum and natural gas deposits, we lack to see such resources due to Turkey's unique geology. Same goes for hard coal as well. Turkey can only meet the demand with lignite as a fossil energy source. The information regarding lignite reserves are given in Table 4.19 which is obtained from the Coal Sector Report (Lignite) (GCTC, 2013).

In this section, previous performance of Turkey regarding energy industry is aimed to be put forth. With BUEMS model the energy sector will be projected to 2052, and the change from 1990 to 2052 will be observed. In the following sections the BUEMS modeling framework and the results that belong to the BUEMS_TR model will be provided.

Table 4.19. Current lignite reserves (tonnes).

Organizations	**Visible**	**Probable**	**Possible**	**Total**
EGC	7.467.788.000	133.706.000	2.964.000	7.604.458.000
GDTC	1.891.434.000	184.005.000	25.030.000	2.100.469.000
MTA	2.371.000.000			2.371.000.000
Private sector	1.680.000.000			1.680.000.000
Total	13.410.222.000	317.711.000		13.755.927.000

5. THE BUEMS MODELING FRAMEWORK

BUEMS modeling system is an optimization model built in a bottom-up structure to optimize investments in energy sector for specific goals and defined constraints. Model outputs data that enables decision makers to observe long-term effects of investment alternatives. These effects are not limited to financial frame, but includes greenhouse gas emissions.

In trying to provide a comprehensive perspective into the analysis, various approaches and methodologies have resorted as explained in Section 2. The methodological diversities of modeling frameworks have led to a broad literature on energy economy environment modeling. These models have different features and are often based on diversified approaches. Despite there have been numerous modeling approaches proposed, they suffer from several major drawbacks:

Even though numerous models have been suggested until now, those models lack practicality of usage because of their demand for the vast amount of data, their inflexibility which limits modelers' options to work with and their inability to detect every relationship within the model.

To overcome the above-mentioned obstacles, this thesis proposes BUEMS modeling framework. The main hallmark of BUEMS modeling is that it's designed to reflect Turkish energy system. BUEMS modeling framework is structured with a bottom-up systematic approach that accompanied by a technology-rich structure. It encompasses entire of the value chain of the energy sector. It includes all the phases of the value chain form extraction of primary energy resources, processing with conversion technologies and consumption of the energy by end use energy sectors.

Technologies in BUEMS, are specially configured to define Turkish Energy Sector. With its flexible structure, BUEMS allows additional analysis for Turkey. BUEMS is built to satisfy the need for a national model representing local technology structure.

BUEMS uses GAMS programming language to model Turkish energy system. As it doesn't use any proxy model, any addition to the model can be easily applied according to needs.

The purpose of BUEMS modeling system is facilitating the creation of the model structure which will require a minimum level of data. The primary objective is obtaining meaningful and trustworthy results by modeling the energy sector with the highest factualness.

One of the features that separate BUEMS from various similar modeling approaches is that it reports the whole formulation explicitly within the thesis. Thus all connections such as fuel consumption and technological investment decisions can be explained. Additionally, the model is designed to represent energy sector as realistically as possible by using minimum data. Hence, it aims to diminish the time spent on gathering and compilation of the data.

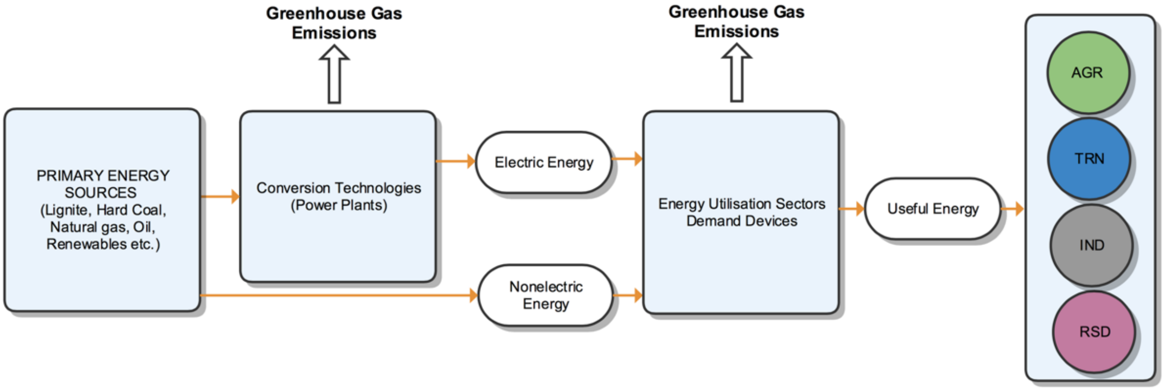


Figure 5.1. General energy and CO_2 emissions flowchart.

Another innovation coming with BUEMS modeling approach is that it enables new technologies to measure the "supply shock" effect inside the model. BUEMS working mechanism, the structure of data, parameters and information concerning the variables used within the model are also explained throughout the study.

5.1. Theoretical Background

This section begins by laying out the theoretical dimensions of the BUEMS modeling framework to provide a basic understanding on the interaction of energy, environment and economy.

As explained before, there are two main approaches of modeling frameworks have to lead to a broad literature on energy economy environment modeling according to the level of aggregation as bottom up and top down. They differ mainly with respect to the structure of technologically based treatment of the energy system and the theoretically consistent description of the general economic system.

Bottom-up models include a partial equilibrium representation of the energy system, describing it in great detail and try to find the least-cost combination of energy technologies to meet energy demand that restricted by technological availability, the potential of energy sources, emissions, etc.

In this study, the proposed modeling framework is designed with a bottom-up perspective. The BUEMS model attempts to determine the supply of the primary energy resources (energy trade option is also available) accompanied by investment and operating that constitutes an energy system to meet the useful energy demands over the pre-specified time horizon at minimum cost.

BUEMS model covers all the components of energy system including the supply of primary energy sources. Fuel extraction processes, primary and secondary production of energy resources, trading mechanism, are included into the model to provide the supply of energy carriers into the system that the modeler aims to construct.

BUEMS attempts to solve the model by applying linear programming methodology. The model comes up with an optimal system configuration that meets energy demands over a set of constraints at least cost at each period.

As in the TIMES modeling framework, BUEMS also has "perfect foresight" which implies that model makes decisions in each period while considering the planning horizon with the knowledge of all future events.

Figure 5.2 depicts the general structure that belongs to BUEMS modeling. The boxes denote technologies whereas the connections define the flows of energy carriers. To put it another way, BUEMS model is built upon two basic components. Technologies can be defined as the physical devices that transform a commodity type into another one by processing, converting or transmitting. Technology is a very comprehensive concept within BUEMS modeling system. As mentioned in the definition above, every unit that converts one commodity to another is named as technology such as any importing operation that introduces a primary energy resource to the system, a refrigerator that satisfies the cooling demand from residential and commercial sectors, a passenger car with diesel engine used for transportation.

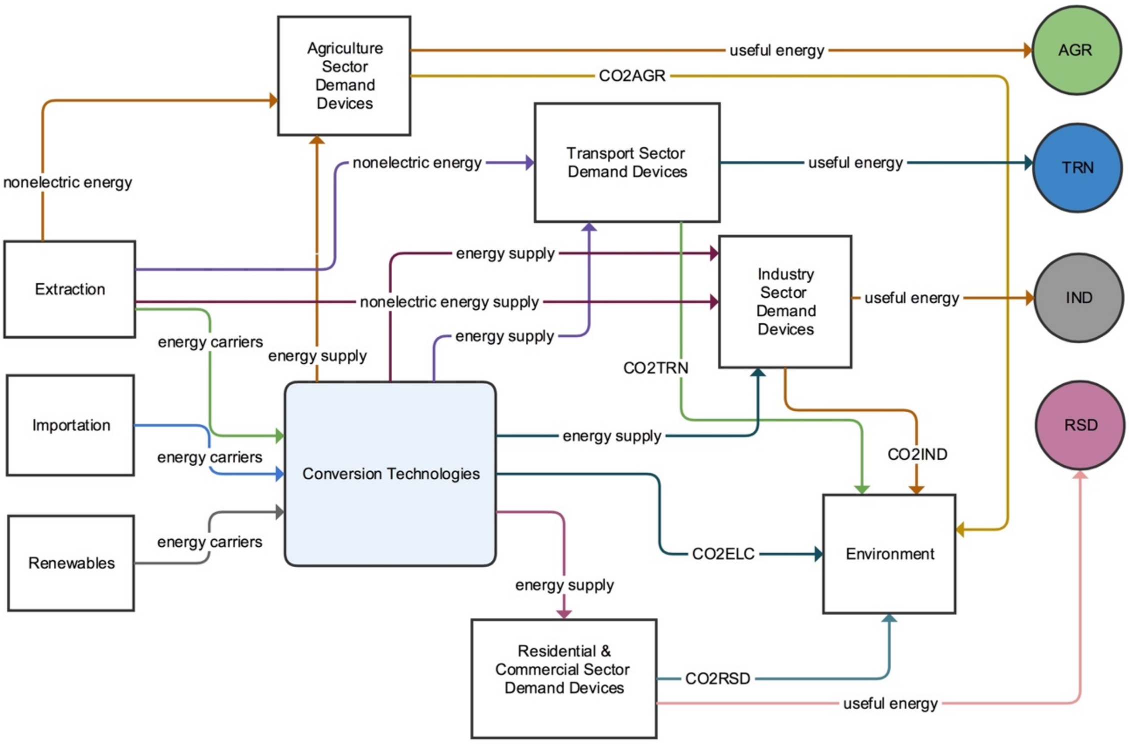


Figure 5.2. The BUEMS Framework.

Each technology is defined in the system by the deployment of parameters. Some of these parameters are common (e.g., new capacity investment cost, operating and maintenance cost, technology start year, salvage value, efficiency). Some of them are valid just for specific technologies (e.g., availability factor is required just for the technologies that have the capacity change under some conditions as in the case of solar power).

The commodity is another important component of BUEMS modeling framework. Commodity consists of any item that belongs to the sets of energy carriers, materials, emissions, monetary terms and energy services that is processed or produced by technology in the model. Another key fact to remember is that when a commodity is processed by a technology, it should be renamed (within BUEMS whenever electricity is used to satisfy an end-use demand through a distribution technology, it is named as a separate commodity for each demand sector. i.e. It will be named TRNELS, if it will be consumed by transportation sector, it will be named as INDELC, when its consumed by industry sector).

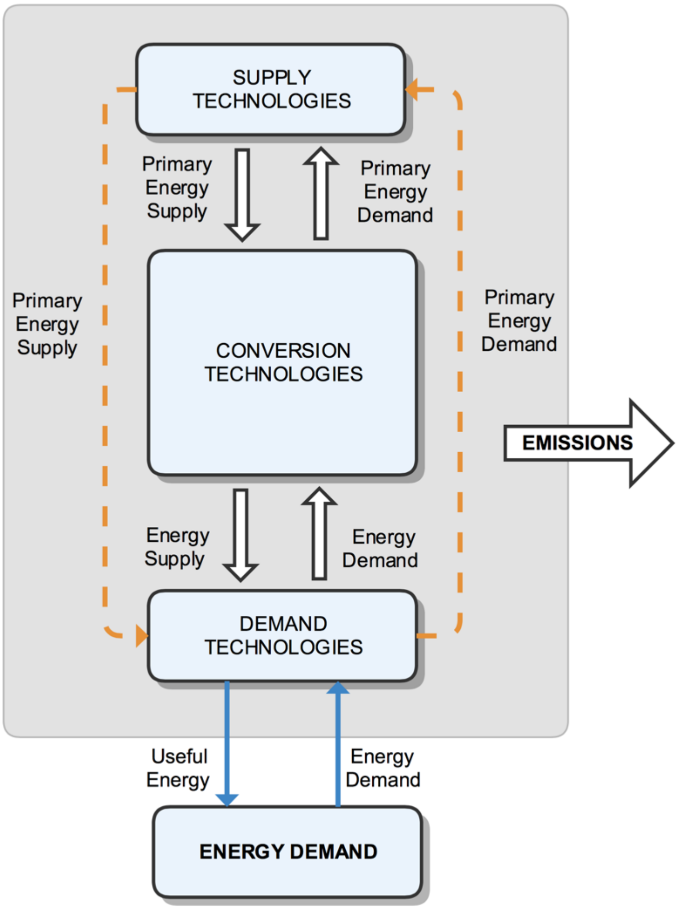


Figure 5.3. Relationships among energy technologies.

As Figure 5.3 shows technologies can be classified into three main categories. The process of energy flows is performed by supply technologies. They provide energy carriers that consumed by conversion technologies. Likewise, in some cases, demand technologies can use primary energy carriers directly (e.g. coal is an option for residential sector space heating). To that end, the technologies have an interaction among themselves to satisfy the useful energy demand in the system.

It is worth mentioning that, in the TIMES modeling framework there exists six different technology categories (CHP, demand devices, electricity generation technologies, energy, HPL and material) as illustrated from Figure 3.2. The total number of technology classes equals to 20 including the sub-sections as NST, IRE, RENEW etc. This variety in technology definitions has a direct effect on the number of equations that constructed to represent the model constraints. This situation brings computational complexity with it. On the other hand, BUEMS model has only three main classes of technologies; supply, conversion and demand.

In the following parts, each group of technology and relationship among them is explained respectively.

5.1.1. Supply Technologies

By definition, technologies convert commodities. This process requires a commodity entry into the technology to be processed. What is special about supply technologies, they do not require any input while providing primary energy sources into the system.

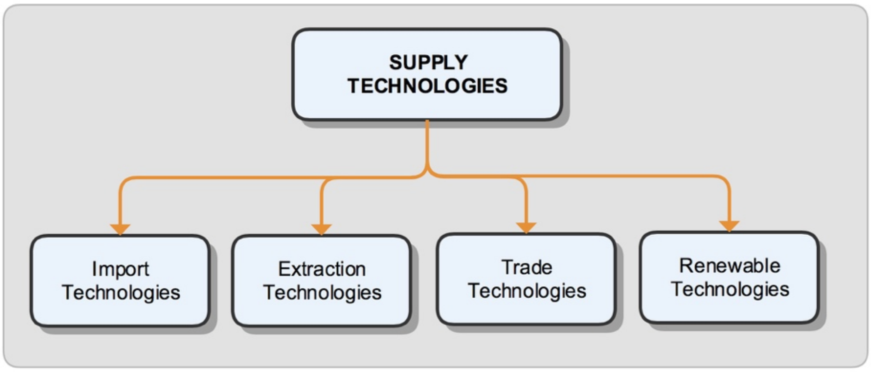


Figure 5.4. Supply technologies.

Supply Technologies' main responsibility is to introduce energy carriers in the energy sector for the first time. It is not possible for the model to perform without any energy source. There exist mainly two options for an energy carrier entering into the system, domestic supply (extraction or other renewable sources (hydropower, solar, tidal, the wind etc.) and import. All types of supply technologies can be considered as energy sinks that have a variable cost, the maximum available resource, lower and upper bounds within each time periods, and cumulative bound.

5.1.2. Conversion Technologies

All of the intermediate technologies that transform one commodity into another energy carrier is called conversion technologies. They modify the type of energy carrier to provide input to another device. Petroleum refineries and electricity generation facilities are modeled as conversion technologies. Main sub-groups that belong to conversion technologies are presented in Figure 5.5.

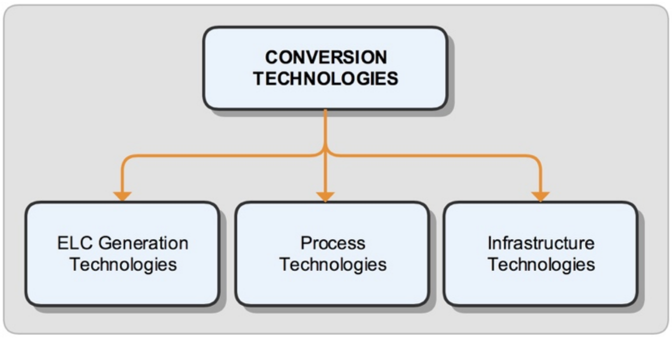


Figure 5.5. Conversion Technologies.

Electricity generation technologies, hence the name, covers any technology that generates electricity. All of the conversion technologies apart from ELC generation and Infrastructure technologies constitutes "process technologies". BUEMS model makes decisions on the variables related to conversion technologies as; new investment level, capacity level, and activity level (Detailed explanations and naming conventions can be given in BUEMS_TR_CD).

BUEMS assumes that new investment on a specific technology can be made only at the beginning of the period, and it will be available for the following periods (including the period that investment takes place) until the end of its technical lifetime (each period a loss of capacity occurs that resulted from depreciation). Taking the existing capacity and new investments into account, the total capacity of the current period is calculated. BUEMS model tunes capacity levels with the parameters reserved for investment decisions, e.g., depreciation rate, efficiency rate, upper and lower bounds on new investments, discount rates (Detailed explanations and naming conventions can be seen from BUEMS_TR_CD).

Infrastructure technologies is added into the model in order to evaluate the construction of LNG storage facility or a new pipeline project that supply primary fuel into the system. Infrastructure technologies differ from trade technologies in a way that they do not require a direct commodity inflow from another region.

These technologies are used not only to provide fuel systems but to evaluate full infrastructure. Their installation costs, availability rates and maximum flow capacities are defined by different set of parameters. Systematically, they are not grouped with supply technologies due to the fact that infrastructure technologies require additional parameters to be represented by the system.

5.1.3. Demand Devices

Demand devices are the final links of the energy system. They produce useful energy to satisfy the final demand requirements that belong to the sectors presented in Figure 5.6 (Another key fact to remember is that, useful energy demands are provided exogenously by the user).

There are some specific qualifications belong to demand devices. In BUEMS model commodity flows are defined regarding energy carriers. However, useful demand requirements can be provided regarding consumption units (e.g. billion lumen lighting demand, billion passenger km traveled). As a result, each demand device should contain a conversion parameter that transforms energy carrier into the system demand requirements.

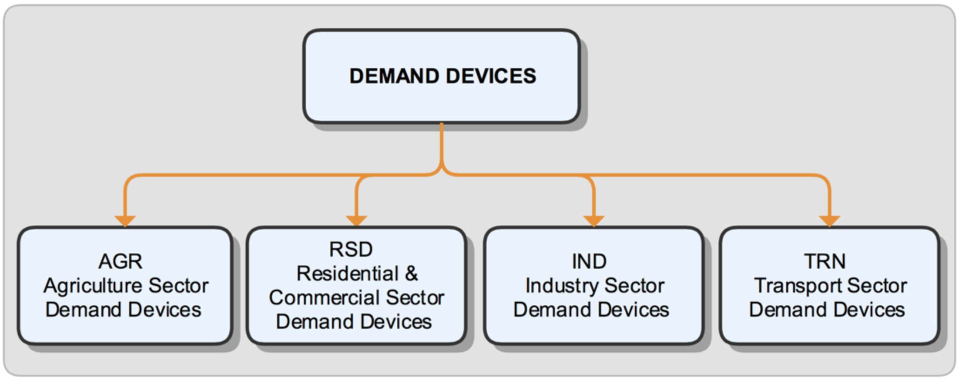


Figure 5.6. Demand technologies.

Similar to other technologies, demand technologies may invest on additional capacity in each period. However, there are no defined operating levels, nor the associated activity variables, for them. Instead, a capacity utilization factor is assigned to each technology. This factor determines the level of capacity that is in use, which implies that the activity of the related demand technologies is to be fixed at a certain percentage of the capacity. Thus, investment and capacity levels are the only variables related to this technology group.

5.2. Model Structure (Sets, Parameters and Variables)

BUEMS model is built in such a way that it includes all components of the energy sector. Therefore, the process starting with the description of the primary energy resource to the model covers the time elapsed between the conversion of fuels to useful energy directly or after being processed and the meeting of final energy demand. Thus, the model tries to find the optimal solution via groups composed of technology and commodity blocks sharing a specific common trait. In this section, all formulations belonging with BUEMS model, the variables, and parameters that comprise those formulations are planned to be explained clearly. Sets which will frequently be used in the following sections and abbreviations belonging to those sets are given in Table 5.1. Descriptions of model variables can be found in the Table 5.2.

Table 5.1. Abbreviations and descriptions of model sets.

Abbreviation	**Description**	**Abbreviation**	**Description**
c	Energy Conversion Technology	p	Any technology of the model
celc	Electricity Generation Technology	l	Time segment
cp	Process Technology	sup	Supply Technology

Table 5.1. Abbreviations and descriptions of model sets (cont.)

Abbreviation	**Description**	**Abbreviation**	**Description**
d	Demand Technology	sexp	Export Technology
dagr	Agriculture Sector Demand Technology	simp	Import Technology
dind	Industry Sector Demand Technology	smin	Mining Technology
dmd	Demand service	srnw	Renewable Technology
drsd	Residential and Commercial Sector Demand Technology	t	Time period
dtrn	Transport Sector Demand Technology	z	Emission type
e	Energy source	y	Year
k,c ∪ d	Energy Conversion and Demand Technologies		

Table 5.2. Descriptions of model variables.

Variable	**Description**	**Variable**	**Description**
sup(s,t)	Supply Level of Supply Technology s	inv(d,t)	Investment Level of Demand Technology
sup(simp,t)	Supply Level of Import Technology s	inv(dagr,t)	Investment Level of Agriculture Sector Demand Technology
sup(smin,t)	Supply Level of Mining Technology s	inv(drsd,t)	Investment Level of Residential Sector Demand Technology
sup(srnw,t)	Supply Level of Renewable Technology s	inv(dind,t)	Investment Level of Industry Sector Demand Technology
sup(sexp,t)	Supply Level of Export Technology s	inv(dtrn,t)	Investment Level of Transport Sector Demand Technology
cap(c,t)	Capacity Level of Energy Conversion Technology	inv(clec,t)	Investment Level of Electricity Generation Technology
cap(d,t)	Capacity Level of Demand Technology	inv(cp,t)	Investment Level of Process Technology
cap(dagr,t)	Capacity Level of Agriculture Sector Demand Technology	ems(v,t)	Emission Level of Emitter
cap(drsd,t)	Capacity Level of Residential Sector Demand Technology	act(cp,t)	Activity Level of Process Technology
cap(dind,t)	Capacity Level of Industry Sector Demand Technology	act(ce,t)	Activity Level of Energy Generation Technology
cap(dtrn,t)	Capacity Level of Transport Sector Demand Technology		

5.2.1. Objective Function

In BUEMS modeling framework, the objective function is the sum of discounted value of net annual costs. At the end of each period, the system obtains costs and revenues arisen from some investment and fuel consumption activities. Total discounted annual cost of a period is calculated by summing over all of the costs incurred due to the consumption and usage of model elements (fuel consumptions, technologies, demand segments, environmental variables, etc.).

$$\min tcost = \sum_{t} anncost(t) \tag{5.1}$$

where,

- $anncost(t)$: total annual cost of period t (discounted to the base year)
- $tcost$: total system cost (discounted to the base year)

BUEMS model has been enriched by some features that make it more efficient compared to similar modeling mechanisms. In BUEMS model each period covers exactly 5 years. The modeler is allowed to change the length of the period on the condition that each of them should cover same number of years. It is assumed that the investments made within the period are ready to be used for that period. With these two characteristics it eases not only mathematical formulation but also calibration phase for the modeler. Years covered within periods can differ within the TIMES modeling framework. As a result of this flexibility, the investments can be used by the system periodically and gradually. Hence, usable capacity for each period has high investment costs, and new investments are mathematically complicated. This situation narrows the flexibility of modeler in calibration phase. Even small changes within the model can result in "infeasible" solutions. Consequently, this prolongs the building phase of a model that can be usable, and that can give realistic results.

5.2.2. Total Annual Cost

Total annual cost of the system consists of five main categories presented in Figure 5.7 and the formulation is presented in Equation 5.2.

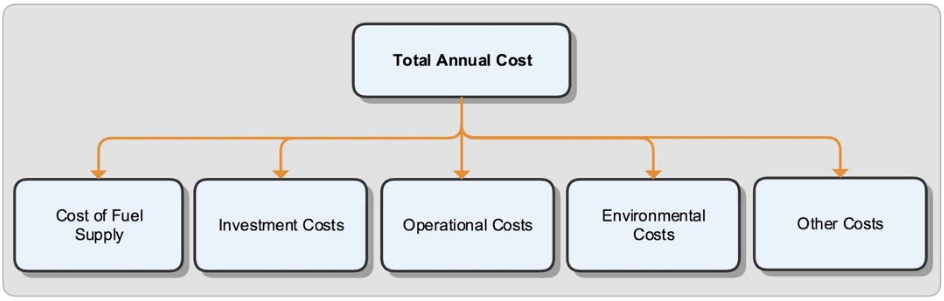


Figure 5.7. Categories of total annual cost.

$$\min tcost = \sum_{t} supcost(t) + addcost(t) + envcost(t) + anncost(t) + invcost(t) + opercost(t) \tag{5.2}$$

where,

- $addcost(t)$: total annual additional costs at period t (discounted to the base year),
- $discost(t)$: total annual cost of period t (discounted to the base year),
- $envcost(t)$: total annual environmental costs at period t (discounted to the base year),
- $invcost(t)$: total annual investment costs at period t (discounted to the base year),
- $opercost(t)$: total annual operational costs at period t (discounted to the base year),
- $supcost(t)$: total annual supply costs at period t (discounted to the base year).

The cost of fuel supply is defined as the sum of all purchases arisen from fuel procurement at period t (including all of the transmission and distribution costs of energy carriers). There is no need to annualize fuel consumptions since it will be realized for each period.

$$supcost(t) = (\sum_{p \in S} usupcost(p,t) \times sup_{(p,t)} + \sum_{p \in ce} edistcost(p,t) \times outent(p,t) \times act_{(p,t)}) \times \sum_{y=1}^{nyrs} (1 + discount)^{-(y-1)} \times (1 + discount)^{-(-startyrs + nyrs \times (t-1))} \tag{5.3}$$

where,

- $edistcost(p,t)$: unit distribution and transmission cost of electricity from technology $p \in ce$ that belong to period t,
- $outent(p\ t)$: level of output generation per unit activity of technology p that belong to period t,
- $usupcost(p,t)$: unit supply cost of technology $p \in s$ that belong to period t.

"Investment cost" can cover a year or a period. However, some costly investments such as the plantation of a thermal power station can take as long as a couple of periods. Under such circumstances, annualization of investment costs should be done first. All maintenance and repair expenses (regardless of it is fixed or variable) due to the use of each type of technology are analyzed under "Operational cost" title.

"Investment cost" includes payment amount per one unit of capacity increase. Investment cost is distributed evenly throughout the lifespan of the technology with the help of "capital recovery factor (CRF). The CRF value is calculated by using equivalent annual cost formula as given in Equation 5.4. Details of the calculation and explanations concerning variables that belong to investment cost are presented in Equation 5.5.

$$crf(p) = \frac{discount(p)}{1-(1+discount(p))^{-life(p)}} \tag{5.4}$$

where,

- $crf(p)$: capital recovery factor of technology p,
- $discount(p)$: discount rate of technology p.
- $life(p)$: lifetime of technology p.

$$\begin{aligned} cost_{inv(p,t)} = {} & crf(p) \times (1+discount)^{-(-startyrs+nyrs\times(t-1))} \times (inv_{cost(p,t)}) \\ & + edistinv(p,t) + etraninv(p,t)) \times fraclife(p) \\ & - salvcost(p,t) + decomcost(p,t) \end{aligned} \tag{5.5}$$

where,

- $crf(p)$: capital recovery factor of technology p.
- $decomcost(p,t)$: the decommissioning cost of technology p at period t.
- $edistinv(p,t)$: unit investment cost for electricity distribution system of technology p at period t.
- $etraninv(p,t)$: unit investment cost for electricity transmission system of technology p at period t.
- $fraclife(p)$: the last period fraction rate,
- $inv\_cost(p,t)$: unit investment cost of technology p at period t.
- $salvcost(p,t)$: the unit salvage cost of technology p at period t.

$$salvcost(p,t) = \frac{\dfrac{1-\left(1+discount(p)\right)^{-nyrs+\frac{life(p)}{nyrs}-npers-1}}{(1+discount(p))^{nyrs\times(npers+1-t)}}}{1-(1+discount(p))^{-life(p)}} \times (inv\_cost(p,t+edistinv(p,t)+etraninv(p,t))) \tag{5.6}$$

"Other Operational Cost" item covers all of the cost items that resulted from all operational and maintenance costs. They have a direct relation with the technology capacities so they are calculated with respect to the volume of the remaining capacity level. Since this figure consists of both fixed and variable operational and variable cost values, they are all aggregated for period t over all of the technologies (Demand devices has different structure comparing to other set of technologies. They can be constructed with an input and an output that have different unit factors. Under this case, the formulation also has unit conversion factor).

$$\begin{aligned} opercost(t) = (&\sum_{p\in c\cup c\ddot{u}d} fixom(p,t) * cap(p,t) \\ &+ \sum_{p\in c} varom(p,t) * act(p,t) + \sum_{p\in d} varom(p,t) * ucf(p,t) \\ &* cf(p,t) * cap(p,t)) \\ &* \times(1+discount)^{-(-startyrs+nyrs\times(t-1))} \end{aligned} \tag{5.7}$$

where,

- $cf(p,t)$: capacity utilization factor that belong to technology p at period t.
- $fixom(p,t)$: fixed operating and maintenance cost per unit activity that belong to technology p at period t.
- $varom(p,t)$: variable operating and maintenance cost per unit activity that belong to technology p at period t.
- $ucf(p)$: unit conversion factor that belong to technology p.

Additionally, costs under “environmental” title, does not affect the goal function if a systematic “penalty” is not defined for a greenhouse gas emission. In the model, two different variables are assigned for each annual cost class. Those variables are used for defining discounted and undiscounted expenses.

5.2.3. Model Constraints

As stated before, BUEMS model is an energy-economy-environment model constructed by optimization principles of the BOTTOM-UP model group. Within this framework, the model needs to comply with the constraints set while trying to optimize the objective function. As it can be seen in Figure 5.8, constraints are combined into six different groups.

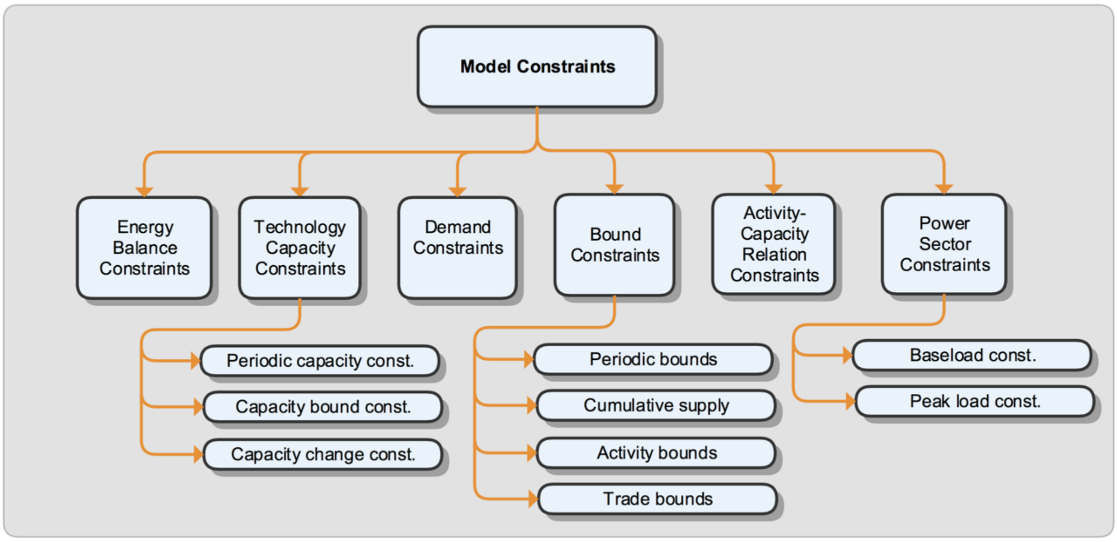


Figure 5.8. Set of BUEMS model constraints.

Energy balance constraints: this constraint makes sure that any energy resource stays below the total supply level of that resource. This constraint set is defined separately for each energy resource. The technologies that supply the energy source through production and/or trade are presented as the upper bound of consumption. Summation of the technologies that export and/or produce the energy source constitutes the right-hand side of the energy balance constraint. The parameter definitions and the formulation of energy balance constraint are presented in Equation 5.8.

$$\begin{aligned}
&\sum_{p \in p_e \cap s} sup_{(p,t)} + \sum_{p \in p_e \cap c} outent(p,t) \times act(p,t) \\
&\geq \sum_{k \in k_e \cap s} inpent(p,t) \times sup(p,t) \\
&+ \sum_{k \in k_e \cap c} inpent(p,t) \times act(p,t) \\
&+ \sum_{p \in k_e \cap d} inpent(p,t) \times cf(p,t) \times \frac{capunit(p)}{eff(p,t)} \times cap(p,t)
\end{aligned} \tag{5.8}$$

where,

- $eff(p,t)$: efficiency rate that belong to technology p for unit activity at period t.
- $inpent(p,t)$: level of input required by technology p for unit activity at period t.
- $outent(p,t)$: level of output generated by technology p for unit activity at period t.

In the TIMES modeling framework, energy balance constraint is more comprehensive due to the sets of technologies. As mentioned before, although the TIMES modeling framework has numerous technology classes, in BUEMS the formulations differs only for three basic technology sets (conversion technologies, demand devices and supply technologies). In the production and the consumption side of the energy balance constraints, as the technology classes increases, the energy balance equations have to include more parameters, which results in computational complexity.

Technology capacity constraints: Constraints for technologies can be placed with three different ways in BUEMS. First one of these belongs to “periodic capacity constraints” class. With this constraint total, ready-to-use capacity for each period is held under control. The total capacity of investments which are previously planted and still haven't concluded its technological lifespan and the total capacity of new investments occurred during the period should be equal to the total capacity of that period as presented in Equation 5.9.

$$cap(p,t) = resid(p,t) + \sum_{h=u(p)}^{t} (inv_{(ph)} - cdf(p) \times inv(p,h) \times (t-h) \times \frac{nyrs}{life(p)} \tag{5.9}$$

where,

- $cap(p,t)$: total capacity that belong to technology p at period t.
- $resid(p,t)$: level of residual capacity that belong to technology p at period t.

Due to the fact that the TIMES modeling framework has variable periods, an investment can be made any year of the period and also this creates a complexity. A useful lifetime of an investment can end on any year within a period. Then the cases mentioned in Section 3.3.3 are also evaluated for technology capacity constraints (the size of the project; small-large, the structure of the investment; progressive-nonrepetitive/repetitive). Under such a complexity 4 different technology capacity constraint set is required in the TIMES modeling framework whereas in BUEMS, more straight forward structure is set to control capacity constraint. The structure of the TIMES modeling framework that requires incremental investments is claimed to provide realism to the cost profile.

Capacity change constraints: This constraint ensures that the change in following periods is limited to a certain percentage. The increase and decrease in capacities are taken under control by "growth" and "decay" constraints respectively. Hence, the model is allowed to behave more realistically. This constraint set is constructed to control the capacity that belong to two consecutive periods. This constraint set prevents model to make investment decisions that creates a change (whether increase or decrease with respect to the previous period) that is not allowed. Allowable range is provided into the model as "percentage of previous period" as presented in Equation 5.10 for the lower bound for investment level and Equation 5.11 for the upper bound for investment level.

$$cap_{(p,t+1)} \geq cap_{(p,t)} \times lbr(p,t+1)^{nyrs}, p \in c \cup d \tag{5.10}$$

$$cap_{(p,t+1)} \leq cap_{(p,t)} \times ubr(p,t+1)^{nyrs}, p \in c \cup d \tag{5.11}$$

where,

- $lbr(p,t)$: Annual decay rate that belong to the capacity of technology p between period t and $t+1$.
- $ubr(p,t)$: Annual growth rate that belong to the capacity of technology p between period t and $t+1$.

In order to control the capacity change into the model throughout the planning horizon, capacity bound and capacity change constraints are also added into BUEMS model. By these two set of additional constraints, the change in the total capacity from one period to another is only allowed to be installed under pre-defined range. Thus, sudden peaks or declines in the capacity instalments will be prevented. As the total cost within the system is high, small cost variations in investments are negligible for the modeler to compensate its extra burden during calibration.

Demand constraints: This constraint ensures that minimum capacity to meet the demand for any energy resource is installed. It is added to the model for each type of demand separately. Related formulation and variable explanations are given in Equation 5.12.

$$\sum_{p \in d_{dp}} outent(dp)(p,t) \times capunit(p) \times cf(p,t) \times cap_{(p,t)} \geq demand(dp,t), p \in d_{dp} \tag{5.12}$$

Bound constraints: This constraint is set to create an upper bound of an activity or a commodity. The bound can be set to cover whole planning horizon or just for a specific period.

Periodic bound: This bound type is used to restrict the decision variables that belong to a technology (such as activity level, capacity level, supply level etc.) The Equations 5.13, 5.14 and 5.15 shows the bounds that are set for "activity levels of technology p for period t.

$$act(p,t) \leq bnd\_up(p,t) \tag{5.13}$$

$$act(p,t) = bnd\_fx(p,t) \tag{5.14}$$

$$act(p,t) \geq bnd\_lb(p,t) \tag{5.15}$$

where,

- $bnd\_up(p,t)$**:** upper bound on activity/capacity/investment/supply of technology p at period t.
- $bnd\_fx(p,t)$**:** Fixed bound on activity/capacity/investment/supply of technology p at period t.
- $bnd\_lb(p,t)$**:** lower bound on activity/capacity/investment/supply of technology p at period t.

Cumulative supply limit: It is created for limiting the total capacity of any technology that will be used throughout the modeling period. Especially for the natural reserves as in the case of coal, total available capacity of the coal deposits is constant within a specific region, so it is impossible to get more than a certain amount in total throughout the modeling horizon. Parameter and constraint formulations are provided in Equation 5.16.

$$\sum_t sup_{(p,t)} \times nyrsper \leq cbnd(p), p \in s \tag{5.16}$$

where $cbnd(p)$ is the cumulative bound on activity/capacity/investment/supply of technology p.

Trade bounds: Import and export operations are defined as technology in BUEMS. Therefore, we can utilize from constraints used for other technologies. This constraint is used to make sure that in scenario analysis, a certain amount of the total reserve of one commodity in the country comes from imports and the formulation is presented in Equation 5.17. To model supply shock case within BUEMS model this set of constraints are also valid for infrastructure investments.

$$\sum_{p\in sim} tsep(p,t) \leq imp\_share(t)\times\sum_{p\in s} tsep(p,t) \tag{5.17}$$

Activity-capacity relation constraints: Total activity of technologies within a period should remain below the maximum capacity of that period. An upper limit is set with the activity-capacity relation constraint as provided in Equation 5.18. Capacity and activity of some technologies can differ from each other in terms of units. Unit conversion factored is added to the constraint to handle differences among units.

$$act_{(m,t)} \leq af(p,t)\times capunit(p)\times cap_{(p,t)}, p\in c \tag{5.18}$$

where,

- $af(p,t)$: annual availability factor of technology $p \in c$ at period t,
- $capunit(p)$: unit conversion factor for technology p.

Power sector constraints: There are two constraints in the electricity sector. These constraints are used to keep electricity production in the system under control.

Baseload constraint: Changing production capacities of some power plants producing electricity (coal-fired power plant, nuclear, etc.) is not feasible. For this reason, this constraint makes sure that certain percentage of the electricity demanded at night is provided by the non-baseload plant in order to prevent other power plants get affected by the fluctuation. Details of the constraint are provided in Equation 5.19.

$$\begin{aligned}&\sum_{p\in ce} outent(p,elc,t)\times qhr\_n(p,t)\times act(p,t)\times baseload(t)\\ &\qquad\geq \sum_{p\in ce\cap baseload\ plants} outent(p,elc,t)\times qhr\_n(p,t)\times r\_act(p,t)\end{aligned} \tag{5.19}$$

where,

- $baseload(t)$: the highest percentage of the baseload power plants in total electricity generation at period t,

- $outent(p,e,t)$: level of electricity generation per unit activity of technology p, $p \in ce$, at period t,
- $night(p,t)$: night time share of electricity generation from technology p at period t.

Peak load constraint: Reserving some of the capacity is needed for meeting the peak demand. With this constraint, electricity production capacity of each period is set higher than the total demand to a certain level. Explanations for the variables and parameters specifically defined for this constraint and formulation is given in Equation 5.20.

$$\begin{aligned} teent(e,t)\times & \left(\sum_{m\in s} peakcon(p,t)\times qhr_{(y)(p,t)}\times sup_{(p,t)}\right. \\ & + \sum_{m\in ce} peakcon(p,t)\times capunit(p,t)\times af(p,t)\times qhr_{y}(p,t) \\ & \times cap_{(p,t)} \\ & \geq \left(\sum_{p\in s} inpent(p,e,t)\times qhr_{(y)(p,t)} * act_{(p,t)}\right. \\ & + \sum_{p\in d} inpent(p,t,e)\times cf(p,t)\times qhr\_(y)(p,t)\times cap_{(p,t)} \\ & \left.\left. /eff(p,t \vphantom{\sum}\right)\right) - \times(1+ereserv(t)) \end{aligned} \tag{5.20}$$

where,

- $ereserv(t)$: peaking reserve factor for electricity generation at period t,
- $inpent(p,e,t)$: level of electricity demand per unit activity of technology p at period t,
- $outent(p,e,t)$: level of electricity generation per unit activity of technology p, $p \in ce$, at period t,
- $peakcon(p,t)$: the fraction of the technology p's capacity at period t that should be credited towards the peaking requirement at period t,
- $teen(e,t)$: transmission efficiency of electricity at period t.

Emission constraints: In “Business as Usual” scenario, there is no need for emission constraints. The model releases emissions proportional to fuel consumption. Emission constraints in Equation 5.21 and Equation 5.22 are activated during emission constraints scenario analysis when a certain amount of decrease in total greenhouse gas emissions or a decrease in accordance with BAU is demanded, or a limitation for a certain sector is placed.

$$totemis(t) \leq emis\_ub(t) \tag{5.21}$$

$$totemis(t) \leq \sum_{z} em(z,t) \tag{5.22}$$

where $totemis(t)$ is the level of total emissions emitted at period t.

5.2.4. Comparison of the BUEMS and TIMES Modelling Frameworks

BUEMS is a bottom-up modelling system inspired by TIMES modelling system. TIMES modelling structure requires high level data, but is developing countries such as Turkey, access to such high level data is extremely difficult, often impossible. BUEMS modelling system reduces the need for data by rearranging some relationships. In this section, TIMES modelling system is selected as benchmark, and basic differences between these two modelling systems are mentioned. Relationships and parameters that will be needed rarely are removed from the model, current relationships are simplified. Additionally, the basic differentiation is due to the fact that technology and commodity sets are re-arranged and implemented in the model as different groups.

Formulations are compared in Table 5.3. As indicated in Figure 3.2, TIMES modelling system, investigates processes under 6 main classes (Combined heat and power technologies, demand devices, electricity generation techniques, energy technologies, heat generation technologies, and material processes) and 13 different classes when sub-classes are included (Combined heat and power technologies, demand devices, electricity generation technologies, energy technologies, heat generation technologies, material processes, electricity generation technologies, distribution systems, night storage systems, storage not night technologies, import-export technologies, refinery technologies, renewable technologies). BUEMS modelling system however, includes only 3 basic process classes as indicated in Figure 5.3. TIMES generates different technology groups for 13 different classes, and manages each group as separate sets. In BUEMS modelling set structure is differentiated for only 3 process classes. Additionally, TIMES modelling system manages electricity production and LTH production as a different commodity class, and to model these, it uses different variables (See Table 5.3). In BUEMS modelling system, constraints that belong to all energy resources are the same. A similar situation is valid for periodic capacity constraint. While TIMES modelling system, defines periodic capacity constraint differently for process, conversion, and demand technologies, BUEMS modelling system does not differentiate constraints. Section 5.2.3, shows how the constraints are formed within BUEMS in detail.

Table 5.3. The comparison of the TIMES and BUEMS formulations

TIMES Framework	**BUEMS Framework**
Discounted Total System Cost	Discounted Total System Cost
Discounted and Annualized System Costs	Discounted and Annualized System Costs
Balance Constraints (for regular energy carriers)	Balance Constraints (for all energy sources)
Balance Constraints (for electricity)	
Balance Constraints (for LTH)	
Periodic Capacity Constraints (for process technologies)	Periodic Capacity Constraints (for all technologies)
Periodic Capacity Constraints (for conversion technologies)	
Periodic Capacity Constraints (for demand technologies)	
Demand Satisfaction Constraints	Demand Satisfaction Constraints
Activity-Capacity Relation Constraints (for standard energy carriers)	Activity- Capacity Relation Constraints (for all energy sources)
Activity-Capacity Relation Constraints (for electricity)	
Activity-Capacity Relation Constraints (for LTH)	
Lower, fixed, upper bounds on technology activity	Lower, fixed , upper bounds on technology activity
Lower, fixed, upper bounds on trade process activity	
Lower, fixed, upper bounds on technology capacity	Lower, fixed , upper bounds on technology capacity
Lower, fixed, upper bounds on technology investment	Lower, fixed , upper bounds on technology investment
Lower, fixed, upper bounds on energy carrier supply	Lower, fixed , upper bounds on energy source supply
Cumulative supply limit	Cumulative supply limit
Lower, fixed, upper bounds on annual output from a conversion technology	
Activity limitation on a multiple output technology	Activity limitation on a multiple output technology
Baseload Constraints for electricity production	Baseload Constraints for electricity production
Electricity Peak Reserve constraint	Electricity Peak Reserve Constraint
LTH Peak Reserve constraint	(Not used)
Total Emissions	Total Emissions
Annual reservoir management for hydro plants	(Not used)
Seasonal reservoir management for hydro plants	(Not used)
Capacity Decay/Growth Constraints	Capacity Decay/Growth Constraints
Supply Decay/Growth Constraints	Supply Decay/Growth Constraints

As mentioned in the sub-section of “objective function” the TIMES modeling framework has additional features to add precision to the cost structure that requires complex mathematical expressions not only in objective function but also to the calculation of costs. The TIMES modeling framework calculates investment and dismantling costs into a form of annual payments. In BUEMS model each type of costs is calculated as “lump-sum” value for a period.

In the TIMES modeling framework, the instalment of new capacity can be made progressively over several years of a time period (if the model makes an investment on a power plant with 6 GW capacity in a period that starts with 2018 and ends in 2025 the physical capacity is spread over 7 years), but in BUEMS model one investment value (as lump sum) is gathered for the considered period. The structure of the TIMES modeling framework that results in increments in the capacity of an investment necessitates different calculations on investment costs under different cases (the size of the project; small-large, the structure of the investment; progressive-nonrepetitive/repetitive).

The TIMES modeling framework as the investment is put in use gradually, complicates the investment formulation when compared with BUEMS. This, makes TIMES model calibration and model building phases to be prone to divert from optimality. BUEMS enables the modeler a more suitable area as it does not require additional information about gradual activation of investments.

In the TIMES modeling framework since the dismantling costs and investments are represented as annual payments, calculation of “ANNCOST” is very tedious (for the TIMES modeling framework calculations please see Section 3.3.5, BUEMS model calculations is provided in Section 5.2.2).

Any important aspect that is worth mentioning is that, salvage cost is calculated by the TIMES modeling framework. The sum of initial year and technical lifetime of an investment is not exactly smaller than EOH, and if the end of its useful lifetime falls within the projection period, the TIMES modeling framework requires different calculations of salvage values for the aforementioned cases. Constant periods and putting investments in use in lump amounts, makes salvage value calculation very easy with BUEMS modeling structure. In

BUEMS, modelers are also allowed to provide salvage value exogenously (For calculations please see Equation 5.6). Even though BUEMS provides such a simplification, the results still vary from the TIMES modeling framework within acceptable values. Hence, it does not result in significant deviations while providing significant ease.

Since the salvage value is also a part of “investment cost” it directly effects the objective function. So the complexity in the calculations of not only the investment cost itself but also of sub-components (salvage value, decommissioning cost etc.) makes the model more breakable under small changes. Optimal model structure can easily be unbalanced and turn into infeasible with small changes as a result of the computational complexity.

Difference between two models are not limited to investment cost and salvage value. BUEMS and TIMES models also differ from each other as set definitions used for calculating supply cost are different. In TIMES modelling system, annual supply cost values consist of 4 main titles, namely energy carrier supply cost, electricity distribution and transmission cost, LTH distribution cost, and LTH transmission cost. For each title, TIMES modelling system generates separate sets, and uses for different parameters for each set (r_tezy(ce,w,t), r_thz(ch,z,t), r_tczhy(ceh,w,t), r_tsep(s,t)). Even though, the calculation of supply cost is the same, it is repeated 4 times (details regarding formulations are given in Equation 3.11). In BUEMS modelling system, LTH modelling is not done. Only two parameters (edistcost(p,t), usupcost(p,t)) namely energy carriers and electricity as indicated in the Equation 5.3 are used.

Another difference between BUEMS and TIMES is in the calculation of “peaking reserve constraint”. As the water modeling isn’t performed, only electricity is included in the formulation of reserve section given in Equation 3.14 (water availability in a reservoir is not included in modeling).

TIMES modeling systems allows new constraints to be added to the model by the user besides the pre-installed constraints. The points that make BUEMS modeling system more flexible than TIMES modeling system are;

- The constraint addition procedures are tedious in TIMES modeling system.
- Additional constraints that are allowed to be added are also limited in TIMES modeling system.

Constraints that are to be added by the used within TIMES modeling system are defined in the system through filters. Filtering system is created by compiling technology or commodity clusters with respect to their common properties. It is constructed over the names or additional properties that are defined in the system belonging to entities in the database (name, consumed fuel, produced fuel, sector info, etc.). If a filter is constructed over a name of a fuel or technology group (In TIMES, many filters work over names), modeler has to be master of the database naming system when constructing a user-defined constraint. For example, if diesel consumption share of passenger cars is desired to be below 40% of total transport diesel consumption, first two different filters have to created (one filter for intersecting technologies starting with “TC” and technologies with input “TRNDIE”, and another filter for all vehicles consuming “TRNDIE). In the second phase, it should be checked if an unprecedented technology or commodity have leaked. If the database naming isn’t suitable for grouping, creating filters in TIMES modeling is pretty hard. Within BUEMS modeling system data is transferred to the model through databases created for each sub-group. A pre-defined variable is available for each group. Thus, the modeler doesn’t need to name a new filter.

Current parameters and technology groups are defined in TIMES modeling system and user cannot make any changes within the system. On the other hand, BUEMS modeling system has an open structure enabling users to redefine the relationships. For example, a constraint preventing electrical car usage before charge stations reach a certain number and capacity, could not be defined in TIMES modeling, however they can be added within BUEMS modeling system. So, infrastructure that has an effect on technology usage or penetration can be analyzed in BUEMS models.

BUEMS is relatively very flexible in output management. TIMES transfers output parameters and variables directly to result database, and does not allow any operation on these values. The users then have to export these results to Excel, and further processes are performed in Excel. BUEMS modeling structure allows users to make changes in the model outputs. For example, the share of hard coal consumption in total fossil fuels, share of imported fuels in total fuel consumption, or share of industry sector in total electricity production, can be directly observed in the outputs.

The main differences between BUEMS and TIMES modeling are that BUEMS modeling structure can be easily handled as it defines technologies and commodities with less number of sets, and BUEMS modeling structure is more flexible as it allows users to define new technologies. Additionally, BUEMS output management allows more detailed reporting when compared with TIMES. Energy-Environment models work with high level data, so this difference allows users to observe inconsistencies in calibration phase.

5.3. Model Calibration

The main purpose of the calibration stage is to reflect all of the characteristics that belong to the Turkish energy sector into the model. In this section, how data is obtained, how it is transformed into a usable structure for the model, and assumptions for demand and production values are explained. Data acquisition is a part of calibration for integrating these data into the model. Primarily, fit of data obtained from different sources are tested for model calibration. Additionally, how data for base year (2012) is organized is explained.

TIMES_TR and BUEMS_TR built in this dissertation require data with broad scope and high detail level. Data regarding current local energy resources (underground reserve levels, seasonal extraction capacities and costs, availability and maximum capacities of renewable energy resources, etc.) and data regarding imported energy types (maximum import level unit supply costs) are needed for fuel type input. Additionally, all power sector is included in the model, so all installed power, and many different detailed data regarding this installed power such as maintenance costs, capacity levels, efficiency levels, etc. are included in the model.

The model constructed includes all processes from energy entering the system to meeting the demands of end user demand sectors. Hence, all energy consuming technologies related to agriculture, transport, residential and commercial and industry sectors are included in the model. In the upcoming sections, which assumptions are included for supply and demand, and with which assumptions the data is inserted into the model are explained.

Due to the vast scope of TIMES_TR and BUEMS_TR models, open source search (official numbers provided by related ministries for each sector, TURKSTAT statistics, data belonging to private companies and organizations i.e. for cement sector, part of the data is obtained from Turkish Cement Manufacturers' Association) and data acquisition from the related organizations continued for approximated 2 years.

First phase of calibration is checking the consistency of related data. In this phase, fit of values announced by two different resources regarding data planned to be used for a specific parameter is checked. For example, vehicle stock, distances covered, and average efficiency values published by Ministry of Transportation, and fuel consumption values of transportation sector published by Ministry of Energy are checked if they are consistent with each other.

After the data entry, a consistency check is performed for the values obtained after the base year 2012 with data announced by official sources. In this phase, it is important whether the installed capacity is sufficient to meet the energy demands of base year, and whether the system electricity production is fitting announced electricity production.

Bottom-up model types have high technological detail level. This makes both data acquisition and data verification very time consuming and cumbersome. Model run I and additional model assumptions had to be made as data compilation and acquisition process took 2 years, and there are some inconsistencies between data acquired from different sources.

Calibration phases are run for both BUEMS_TR and TIMES_TR models. In addition to the calibration phases, BUEMS_TR model results are checked if they are consistent with TIMES_TR model. This phase of calibration is explained in detail in Section 6. Assumptions made for supply and demand side in the model are explained extensively in Sections 5.3.1, 5.3.2 and 5.3.3.

5.3.1. Calibration of Supply

A major calibration issue relates to the comparability between the statistics declared by governmental entities, with TIMES_TR and BUEMS_TR energy model outputs. A fundamental difficulty in comparing the model results is to find the real efficiency values that belong to the residual capacity of the existing technology stocks.

Primary energy resources for reference scenario, including the procurement costs of these resources, end use energy demand (vehicle-km, lighting demand for the residential sector, high-temperature heat demand of paper industry, etc.) are defined in the model for the reference year 2012. Additionally, existing capacities of energy consuming technologies in all sectors considering the all future potential technologies, available capacities of primary energy resources and their potentials are included in the model.

Turkey's dependence on importing energy resources such as petroleum and natural gas is growing as a result of its rapidly increasing energy demand. On the other hand, production opportunities for various renewable energy resources (water, wind, solar, geothermal and others) are available. To model the investment and energy consumption decisions, prices of primary energy resources that introduced into the BUEMS model are presented in Table 5.4.

Table 5.4. Fuel Prices (2012Million $/PJ).

Fuel Type	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Biomass	17,7	17,7	17,7	17,7	17,7	17,7	17,7	17,7	17,7
Biomass (domestic)	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6
Coking Coal (Imported)	17,4	17,4	17,4	17,4	17,4	17,4	17,4	17,4	17,4
Crude Oil	24,7	24,7	24,7	24,7	24,7	24,7	24,7	24,7	24,7
Diesel	17,4	17,4	17,4	17,4	17,4	17,4	17,4	17,4	17,4
Diesel	18,3	18,3	18,3	18,3	18,3	18,3	18,3	18,3	18,3
Electricity	17,9	17,9	17,9	17,9	17,9	17,9	17,9	17,9	17,9
Ethanol	23,2	23,2	23,2	23,2	23,2	23,2	23,2	23,2	23,2
Gasoline	23,4	23,4	23,4	23,4	23,4	23,4	23,4	23,4	23,4
Gasoline	0	0	0	0	0	0	0	0	0
Geothermal	4,8	4,8	4,8	4,8	4,8	4,8	4,8	4,8	4,8
Hard Coal (domestic)	5,3	5,3	5,3	5,3	5,3	5,3	5,3	5,3	5,3
Hard Coal	26,8	26,8	26,8	26,8	26,8	26,8	26,8	26,8	26,8

Table 5.4. Fuel Prices (2012Million $/PJ) (cont.)

Fuel Type	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hydropower	25,8	25,8	25,8	25,8	25,8	25,8	25,8	25,8	25,8
Jet Fuel	25,9	25,9	25,9	25,9	25,9	25,9	25,9	25,9	25,9
Kerosene	25,5	25,5	25,5	25,5	25,5	25,5	25,5	25,5	25,5
Light Fuel Oil	4,8	4,8	4,8	4,8	4,8	4,8	4,8	4,8	4,8
Lignite (domestic)	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5
Lignite	102,6	102,6	102,6	102,6	102,6	102,6	102,6	102,6	102,6
Liquid Hydrogen	0	0	0	0	0	0	0	0	0
LNG	21,5	21,5	21,5	21,5	21,5	21,5	21,5	21,5	21,5
LPG	38,4	38,4	38,4	38,4	38,4	38,4	38,4	38,4	38,4
MSW-1(domestic)	51,2	51,2	51,2	51,2	51,2	51,2	51,2	51,2	51,2
MSW-2(domestic)	66,6	66,6	66,6	66,6	66,6	66,6	66,6	66,6	66,6
MSW-3(domestic)	12	12	12	12	12	12	12	12	12
Natural Gas	1	1	1	1	1	1	1	1	1
Nuclear	1	1	1	1	1	1	1	1	1
Petroleum coke	20,9	20,9	20,9	20,9	20,9	20,9	20,9	20,9	20,9
Residual Fuel Oil	0	0	0	0	0	0	0	0	0
Solar(domestic)	0	0	0	0	0	0	0	0	0
Wind (5.5m/s) (domestic)	0	0	0	0	0	0	0	0	0
Wind (5m/s) (domestic)	0	0	0	0	0	0	0	0	0
Wind (6m/s) (domestic)	0	0	0	0	0	0	0	0	0
Residual Fuel Oil	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6
Solar(domestic)	0	0	0	0	0	0	0	0	0
Wind (5.5m/s)	0	0	0	0	0	0	0	0	0

5.3.2. Calibration of Demand

Demand industries are investigated under five main topics as AGR, TRN, IND, COM, and RSD within the model. Projection values of each sector are modeled according to their respective demand structure (for detailed information, please see Section 4). The agriculture industry is modeled in terms of consumed fuel type as detailed information regarding this industry was not available. Hence, the agriculture industry is organized to meet the five different energy demands (coal, diesel, electricity, natural gas, and renewables).

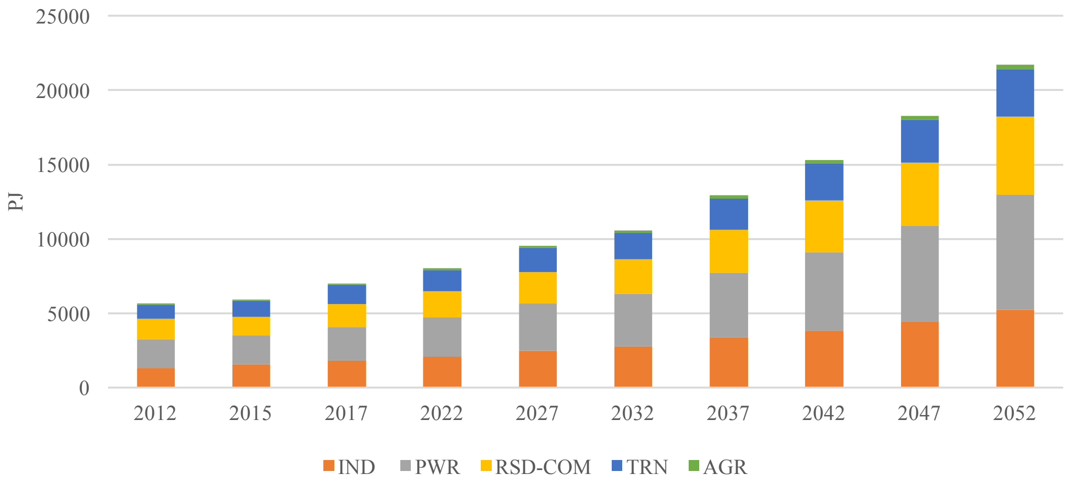


Figure 5.9. Demand projection of TIMES_TR and BUEMS_TR.

In Figure 5.9, it is observed how the demands of industries are shaped. Total demand is 5576PJ in 2012 and forecasted to nearly double this value to reach 10399PJ in 2032, and to reach its peak value of 21416PJ in 2052. Power sector gets the largest share of 35%, followed by industry sector with 26%, and then by residential and commercial sector with 23%. Industry sector consists of 11 main sectors and five main energy demands (process heat, machine drive, facility, feedstock, other heat) of each sector.

So, industry sector is organized to meet 55 different energy classes. The residential and commercial sector is defined to meet nine different demands (residential lighting, space heating, space cooling, etc.). As shown in Figure 5.10 transport sector consists of 6 main topics. BUEMS_TR and TIMES_TR are modeled similarly with a total of 75 demand sub-sectors. Some of the demands are defined directly in terms of PJ, while some are defined in end-use demands such as vehicle km's or lumens (for detailed information, please see Section 4).

Technology stock is defined as the residual capacity to meet energy consumptions indicated in the general equilibrium of the year 2012, which is defined as the base year in the model calibration phase, exactly. By this way, average energy efficiency data of not only technology stock but also stock are obtained.

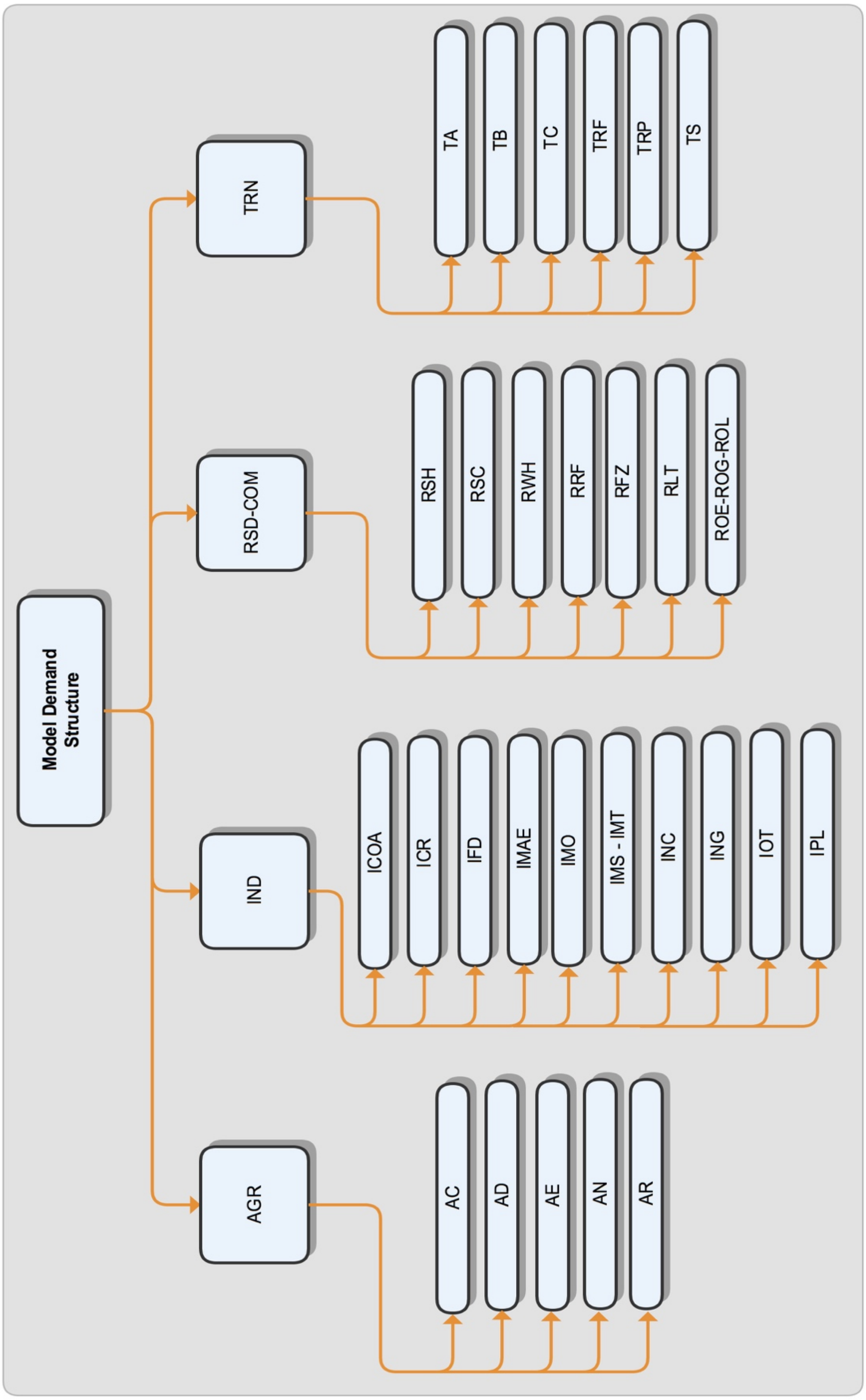


Figure 5.10. BUEMS demand structure.

In order to find sub-divisions of energy demands for end-use demand sectors, statistical data created by Directorate of Renewable Energy and Ministry of Transport, Ministry of Environment and Urbanization, Ministry of Energy and Natural Resource are used. Sub-divisions of stocks of different technologies meeting the same demand type are obtained (vehicle stock of passenger car, residual capacity of power plants etc.) Demand projections of all demanding sectors and parameters of these demands are given in BUEMS_TR_CD.

5.3.3. Calibration of Installed Capacity

The energy required to meet the end use demands of five main sectors using the primary energy sources defined in the model is realized with energy production within the power sector which is defined as an intermediary sector within the model. (For detailed information, please see Section 4.4).

Installed power information in installed capacity calibration announced by Ministry of Energy and Natural Resources (MENR), capacities of all plants that are planned to be built within the model period are added into residual capacity. Electricity production efficiency values are calculated for each plant type in order to sustain a consistency between the fuel consumption of the base year 2012 announced by IEA and MENR, and produces energy data from this consumption. During these calculations, transmission line losses announced by official resources are also taken into consideration.

Refinery sector which is meeting the consumption of petroleum derived fuel for other sectors is included within installed power calibration.

Production efficiencies are calculated to balance the consumed fuels, imported fuels, and fuels processed in local refineries, and presented to related organizations for approval. Maximum and minimum production efficiency intervals are calculated for each output fuel type that will keep the variety of fuel outputs in refinery production under control.

As mentioned before, the refinery sector fuel consumptions are calculated from the general energy balance tables and data obtained from TPRC. Production values for fuel oil, LPG, kerosene, jet fuel-kerosene, benzene, and diesel are forecasted by the model so that the demand of sectors for the projection period are met.

Any incompatibilities between refinery outputs and demand are balanced through import-export activities created within the model.

6. RESULTS

Energy flows are represented with a network description that includes primary energy resources, energy production-conversion technologies and demand devices in the model for a time period of 2012- 2052.

The model is conducted in order to meet five aggregated demand sectors namely: residential, commercial sector, transport sector, industry sector and agriculture. Each of these five sectors are evaluated and modeled separately with specific demand technologies. The underlying cause is to track different behavior of demand categories. For instance, in residential sector, energy requirement arising from certain needs such as lighting, heating and cooling. For the case of industry sector energy requirements, the amount of desired energy type and structure (as Motor Drive and Process Heat) considerably differs that of residential.

Model results are examined in scenario analysis frame. Scenario planning, is an important management and system process that manages the uncertainties of future, and increases the efficiency of strategic planning process.

In this study, scenarios are generated and evaluated using scenario analysis technique. One of the best ways to study uncertain environments is to generate future scenarios. In the planning please, to represent future situations, 3 scenario analyses are performed. These are Business as Usual (BAU), Carbon Emission Tax, and Carbon Emission Bound scenarios.

In BAU scenario it is assumed that status quo is preserved for agriculture, residential and commercial, transport and industry sectors, as well as electricity production sector, and laws and regulations regarding Turkish Energy System valid for base year 2012 until the end of analysis period. Assumptions made for BAU scenario are given in detail in Table 6.1.

In BAU scenario, following additional assumptions are set in addition to the basic constraints that are utilized to tailor the model in accordance with the status of Turkey in base year (2012).

Table 6.1. BAU assumptions.

Sectors	**Assumptions**
Electricity generation sector	For coal, natural gas and hydro power plants; Power plants that are declared to be licensed in the TEIAS 2013 Capacity Projection Report are added to the total installed capacity. In addition to this related production costs are applied according to the delegated legislation with Law no:5346 (Date:29 December 2010 No.6094)
	For solar, wind, geothermal power plants; Power plants that are declared to be licensed in the TEIAS 2013 Capacity Projection Report are added to the total installed capacity. In addition to this related production costs are applied according to the delegated legislation with Law no:5346 (Date:29 December 2010 No.6094)
Electricity Transmission and Distribution	Under the assumption that electrical leakage loss ratio remains stable, 17% will be considered as the ratio of leakage losses for the period of 2017-2052. For base year and 2015 it is assumed to be 14.7% as given in IEA statistics
Transportation Sector	Resource usage and capacity investment decisions are made in accordance with the minimum cost objective function.
Industry Sector	Resource usage and capacity investment decisions are made in accordance with the minimum cost objective function.
Residential and Commercial Sector	In BAU scenario it is assumed that existing building stock has no energy saving resulted from insulation.

BAU scenario accepts that assumptions made in 2012 will continue to be valid until 2052. To observe how Turkish Electricity Sector is shaped against additional policies that will be put into effect by the state, additional scenario analyses are performed.

“Emission Tax” scenario groups enable other analyses on how emission tax is defined in the system, and how recourse consumptions will be shaped in addition to BAU assumptions given in Table 6.1. Emission tax is investigated under 4 different levels, $10, $20, $30, and $50 respectively.

“Emission Bound” scenario group enables analyses on how technology investments, and resource consumptions are shaped when additional emission reduction constraints are enforced over the total emission values obtained from BAU scenario. Emission bound scenarios are investigated under 3 different levels, 10%, 20%, and 30% respectively. Scenarios determined for emission tax and emission bound are given in Table 6.2.

6.1. Model Validation of BUEMS_TR and TIMES_TR

This study is composed of two main sections. Firstly, in order to validate the results of BUEMS_TR model, TIMES-TR model which provides results well accepted by many countries for energy economy environment modeling is built. BAU scenario under the assumptions given in Table 6.1 is analyzed within both models, to show if BUEMS_TR model is giving reliable results. Any data that added into model to structure TIMES_TR and BUEMS_TR models are presented in BUEMS_TR_CD in detail.

Model validation is done in three steps. At the first step, values obtained from TIMES_TR are compared with the numbers announced by the official organizations for the base year 2012. The second phase is the consistency check of TIMES_TR results for the other years with goals, forecasts, and resource potentials announced by official organizations. The third step is the consistency check of BUEMS_TR model results for the base year with the data announced by the official organizations. Additionally, the BUEMS_TR Model results are also compared with TIMES_TR model results for years up to 2052 for consistency.

After TIMES_TR and BUEMS_TR model results are evaluated with total fuel consumption and total emissions, sectoral responses are investigated according to BUEMS_TR results. For the upcoming sections, the abbreviations given in Table 6.2 will be used.

Table 6.2. Scenario nomenclatures.

Nomenclature	**Description**
BAU_TM	TIMES model business as usual scenario results
BAU_BM	BUEMS model business as usual scenario results
CO2_10_TM	TIMES model $10 emission tax scenario results
CO2_10_BM	BUEMS model $10emission tax scenario results
CO2_20_TM	TIMES model $20emission tax scenario results
CO2_20_BM	BUEMS model $20emission tax scenario results

Table 6.2. Scenario nomenclatures (cont.)

Nomenclature	**Description**
CO2_30_TM	TIMES model $30emission tax scenario results
CO2_30_BM	BUEMS model $30emission tax scenario results
CO2_50_TM	TIMES model $50emission tax scenario results
CO2_50_BM	BUEMS model $50emission tax scenario results
BAU_10_TM	TIMES model 10% emission bound scenario results
BAU_10_BM	BUEMS model 10% emission bound scenario results
BAU_20_TM	TIMES model 20% emission bound scenario results
BAU_20_BM	BUEMS model 20% emission bound scenario results
BAU_25_TM	TIMES model 25% emission bound scenario results
BAU_25_BM	BUEMS model 25% emission bound scenario results

For the first step of the validation, it is observed that BUEMS model results are consistent with the 2012 Energy Balance sheet data published by Ministry of Energy and Natural Resources (Please see Appendix B).

For the other analysis period (2012-2052) the announced reserve amounts and maximum capacities are taken into account. TIMES_TR data are accepted to be valid to validate the BUEMS_TR model. For the upcoming sections, BUEMS_TR model, TIMES_TR general model results, and sectoral responses to the BUEMS_TR model are investigated.

6.1.1. Fuel Supply

To evaluate the model results, primarily the differences in consumed fuel types are controlled. Fuel consumptions obtained from TIMES_TR and BUEMS_TR models are given in Table 6.3 and Table 6.4 respectively.

When the differences between two models are investigated, it is observed that the change in consumptions varies from 1% to 10%. In the model salvage value calculation and using a simpler formulation for electricity a production, a decrease in capacities between periods, and limiting the increases are the main reasons why BUEMS_TR results differ from that of TIMES_TR model. The reason of the variation in fuel consumptions are due to the structure of BUEMS which is clarified in Section 5.

Table 6.3. Energy consumption values provided by BAU_TR (PJ).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Asphaltite	6	26	29	33	35	42	50	57	65
Hard Coal	994	1300	1578	2064	2405	3288	3536	3897	4414
Lignite	659	721	952	1210	1395	1704	2670	3853	5107
Electricity	746	866	980	1161	1300	1602	1919	2318	2782
Natural Gas	1542	1969	2201	2446	2799	3106	3384	3753	4268
Nuclear	0	0	0	0	0	0	0	0	0
Diesel	655	861	941	1050	1125	1278	1346	1556	1707
Distillate Oil	9	8	10	10	11	9	13	13	11
Gasoline	79	157	211	293	352	530	812	958	1094
Jet Fuel	162	225	236	266	289	336	387	437	490
Kerosene	2	2	2	3	3	4	5	6	7
LPG	175	140	136	130	125	140	148	170	191
RFO	45	44	43	48	51	50	51	53	56
Petroleum coke	112	154	181	228	260	350	447	567	711
Biomass	146	131	133	196	197	219	213	217	376
Ethanol	2	2	6	8	10	11	16	24	29
Geothermal	97	96	98	101	103	109	114	120	97
Hydrogen	0	0	0	0	0	0	0	0	0
Hydro	202	283	283	284	283	286	288	289	290
Solar	32	36	38	41	44	51	60	68	72
Wind	18	14	12	10	9	12	12	12	12
Crude Oil	1035	2556	2795	3115	3341	3786	3996	4615	5165

Table 6.4. Energy consumption values provided by BAU_BM (PJ).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Asphaltite	6	26	29	33	35	42	50	57	65
Hard Coal	993	1255	1536	2038	2690	2515	3089	3790	4594
Lignite	640	740	1062	1346	1395	1574	2670	3853	5255
Electricity	748	865	982	1176	1299	1601	1914	2311	2781
Natural Gas	1547	1969	2196	2371	2730	3140	3413	3853	4592
Nuclear	0	0	0	0	0	0	0	0	0
Diesel	656	864	941	1050	1127	1279	1347	1624	1817
Distillate Oil	9	5	7	10	11	8	12	13	11
Gasoline	79	157	211	261	348	515	796	928	1064
Jet Fuel	162	225	236	266	289	336	387	437	490
Kerosene	2	2	2	3	3	4	5	6	7
LPG	175	140	136	130	125	140	148	170	190
RFO	54	44	43	48	51	50	51	55	61
Petroleum coke	112	154	181	228	260	350	447	567	711
Biomass	146	131	133	196	197	219	218	254	376
Ethanol	2	2	6	8	10	11	16	24	29
Geothermal	92	96	98	101	103	109	114	120	97
Hydrogen	0	0	0	0	1	0	0	0	0
Hydro	208	283	290	302	310	322	334	339	345
Solar	32	52	54	57	60	67	76	84	75
Wind	22	18	18	18	18	18	18	18	18
Crude Oil	995	2556	2780	3109	3344	3787	3997	4608	5147

As seen from Figure 6.1, BAU_TM and BAU_BM scenario results vary from 1.02% to 9.25%. Average variation for the period 2012-2052 is 4.53%. Thus, the main fuel consumptions indicate that the results obtained by BUEMS is reliable.

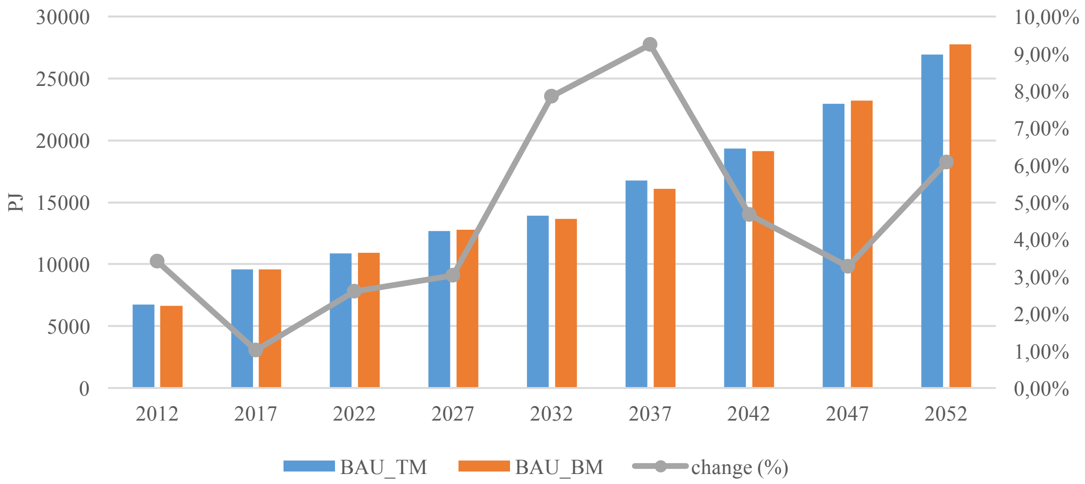


Figure 6.1. Comparison of BAU scenario fuel consumption values.

In the following sections, the discussion of sectorial fuel consumptions and associated emission values belong to BUEMS is given (Detailed data of scenario outcomes associated with TIMES and BUEMS is provided in BUEMS_TR_CD).

6.1.2. Agriculture Sector

The total energy requirement for agriculture sector is equal to 81,3 PJ in 2012 and expected to grow on 305 PJ in 2052. For the following years within the period, the demand is projected by considering the GDP change declared by OECD. Since no additional information on technology usage in agricultural activities, the demand is set upon the final consumptions namely on geothermal, electricity, diesel, hard coal and natural gas.

The agriculture industry is modeled based on general energy consumptions, so there are no differences observed between TIMES and BUEMS model results.

Diesel has the major share of consumption (51%) and is followed by electricity (26%). When the energy efficiencies are investigated, it is forecasted that there will be a 12%

increase until 2030, and 20% increase until 2050 in coal consuming technologies. An average of 7% efficiency increase is observed for diesel consuming technologies until the end of the analysis period.

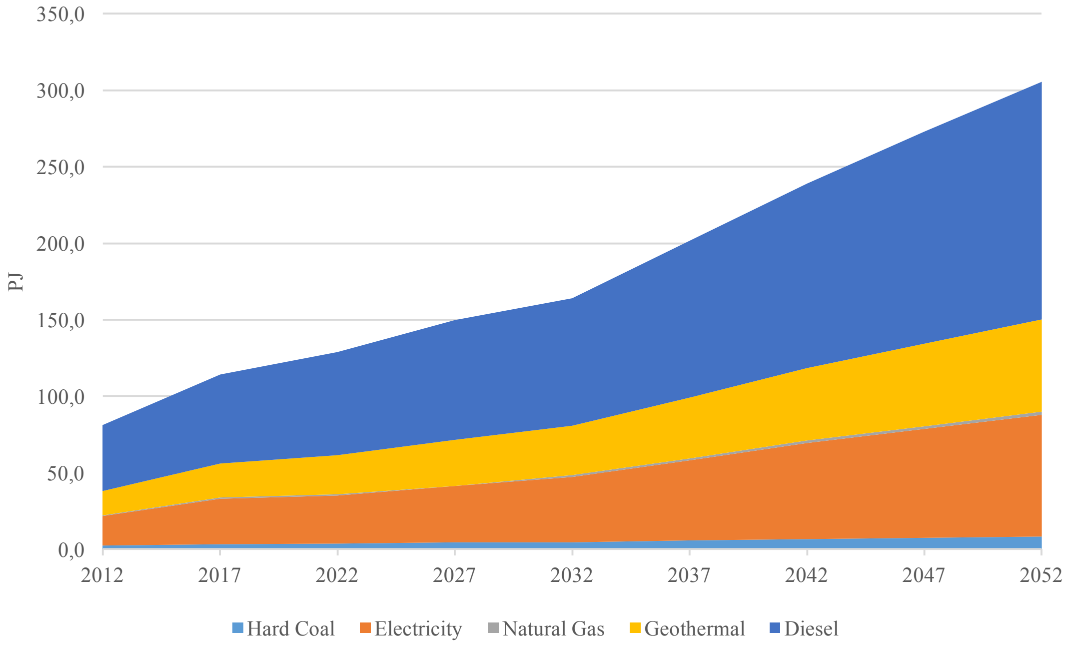


Figure 6.2. Agriculture sector fuel consumptions under BAU (PJ).

6.1.3. Industry Sector

Production values based on industry sectors are obtained from the reports of TUIK and other national and international organizations that are based on TUIK values. For industries such as foods and chemistry which has high product variety and consequently for which is impossible to forecast based on quantities, production values in monetary units (TL) are used. Sectors for which the outputs are easily observed such as iron-and-steel and cement, energy intensities per ton is calculated. Energy consumptions for the base year are derived from these values. Figure 6.3 shows demand forecasts for 11 sectors[1]. The demand projections are forecasted taking into account the expectancies of an increase in GDP. So, the highest increase in consumption is also expected industry sector. Total demand was

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[1] Steel Industry is divided two sub-sector namely primary and secondary

approximately 1334PJ in 2012, and is expected to reach 6763PJ in 2052 if no improvements are observed in the technology used.

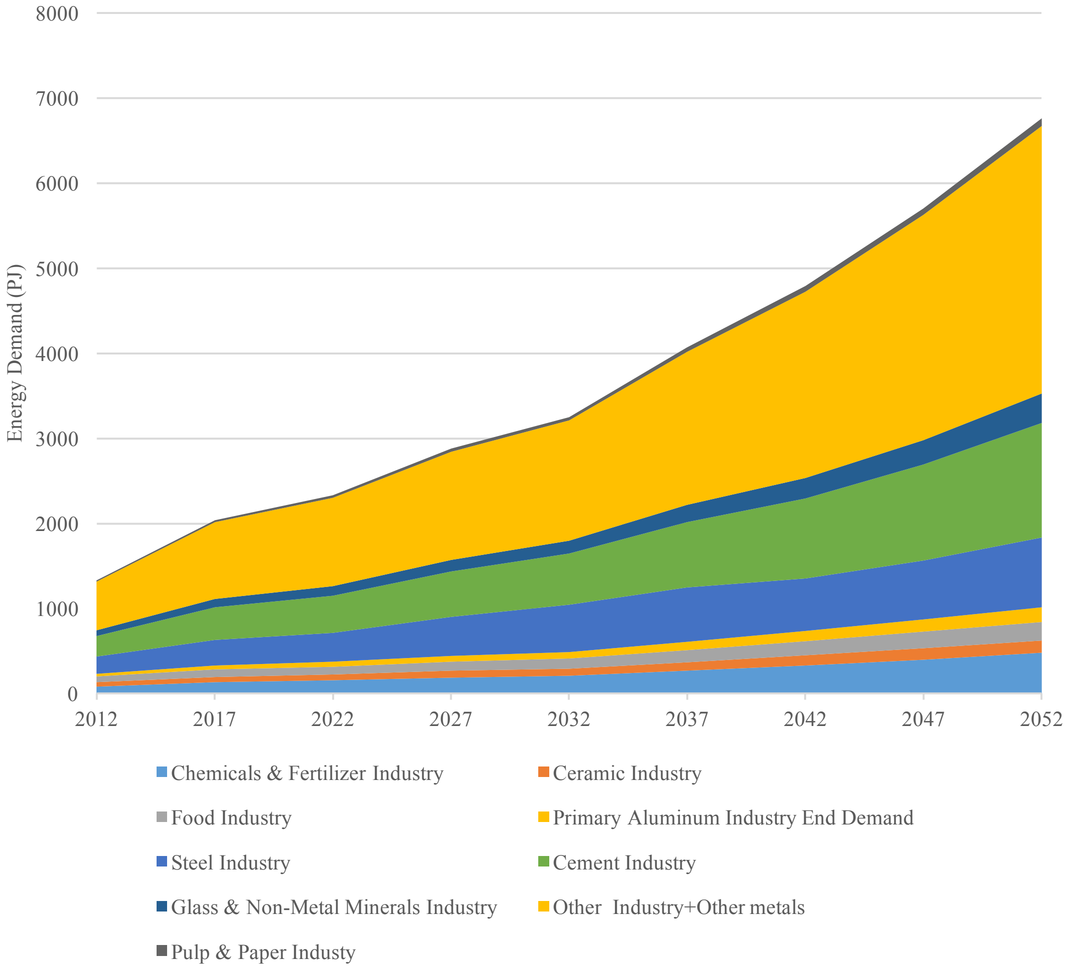
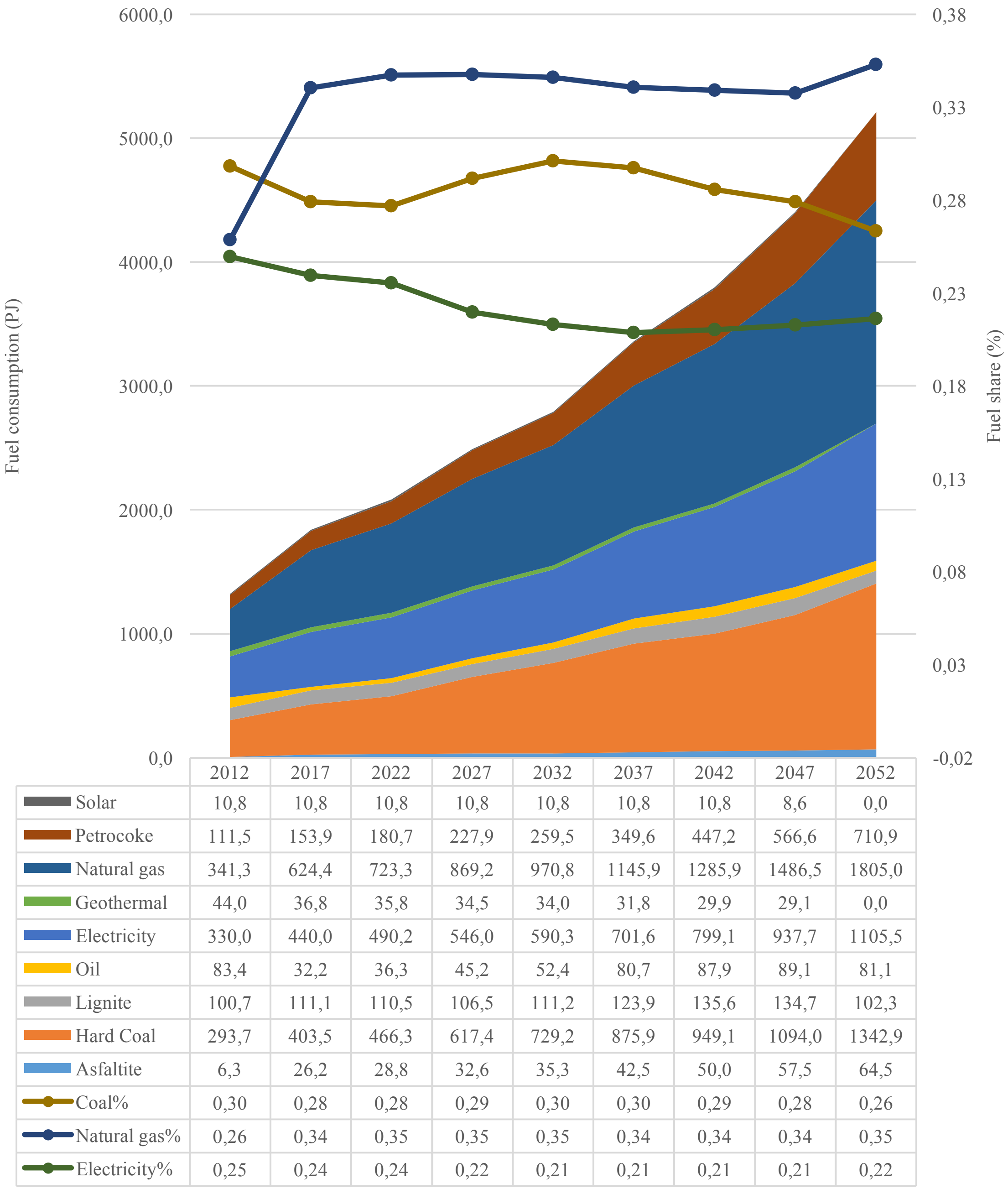


Figure 6.3. Demands of industrial sectors (PJ).

As portrayed in Figure 6.3 in the BAU scenario, total energy consumption is expected to reach 5213PJ in BAU_BM on the other hand BAU_TM predicts total fuel consumption to hit 5217PJ. The hard coal consumption does not exceed 30% of the total primary energy consumption. The share of natural gas consumption increases linearly through the period 2012–2052, reaching 35 per cent by 2027. Along the time horizon, the electricity consumption declines, from 25 per cent in 2012 to 22 per cent in 2052. In 2052, lignite consumption covers only 3 per cent of total fuel consumption which corresponds to 102PJ.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Solar	10,8	10,8	10,8	10,8	10,8	10,8	10,8	8,6	0,0
Petrocoke	111,5	153,9	180,7	227,9	259,5	349,6	447,2	566,6	710,9
Natural gas	341,3	624,4	723,3	869,2	970,8	1145,9	1285,9	1486,5	1805,0
Geothermal	44,0	36,8	35,8	34,5	34,0	31,8	29,9	29,1	0,0
Electricity	330,0	440,0	490,2	546,0	590,3	701,6	799,1	937,7	1105,5
Oil	83,4	32,2	36,3	45,2	52,4	80,7	87,9	89,1	81,1
Lignite	100,7	111,1	110,5	106,5	111,2	123,9	135,6	134,7	102,3
Hard Coal	293,7	403,5	466,3	617,4	729,2	875,9	949,1	1094,0	1342,9
Asfaltite	6,3	26,2	28,8	32,6	35,3	42,5	50,0	57,5	64,5
Coal%	0,30	0,28	0,28	0,29	0,30	0,30	0,29	0,28	0,26
Natural gas%	0,26	0,34	0,35	0,35	0,35	0,34	0,34	0,34	0,35
Electricity%	0,25	0,24	0,24	0,22	0,21	0,21	0,21	0,21	0,22

Figure 6.4. Industry sector fuel consumptions under BAU_BM(PJ).

To compare the model results of TIMES_TR and BUEMS_TR, TIMES_TR model results are given in Figure C.1 in Appendix C. Minor differences are observed under BAU scenario. For example, BUEMS_TR forecasts that energy consumption will reach a maximum level of 1805PJ, while TIMES_TR forecasts that same value as 1796PJ. When oil consumption is investigated, 2032 consumption is 80,7 in BUEMS_TR, which corresponds to 72,5 in TIMES_TR.

Table 6.5. Industry sector natural gas consumption values (PJ).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Chemicals and Fertilizer Industry	57	99	117	130	163	195	232	281	331
Primary Aluminum Industry End Demand	19	30	35	37	43	48	57	69	78
Steel Industry	18	15	21	24	38	24	38	45	50
Secondary Steel Industry	11	23	48	55	68	76	90	109	125
Cement Industry	6	22	27	29	36	42	49	57	66
Glass and Non-Metal Minerals Industry	36	54	62	68	81	89	98	110	122
Other Industry	188	465	542	607	688	774	876	1078	1215
Pulp and Paper Industry	5	15	18	21	27	33	41	50	59

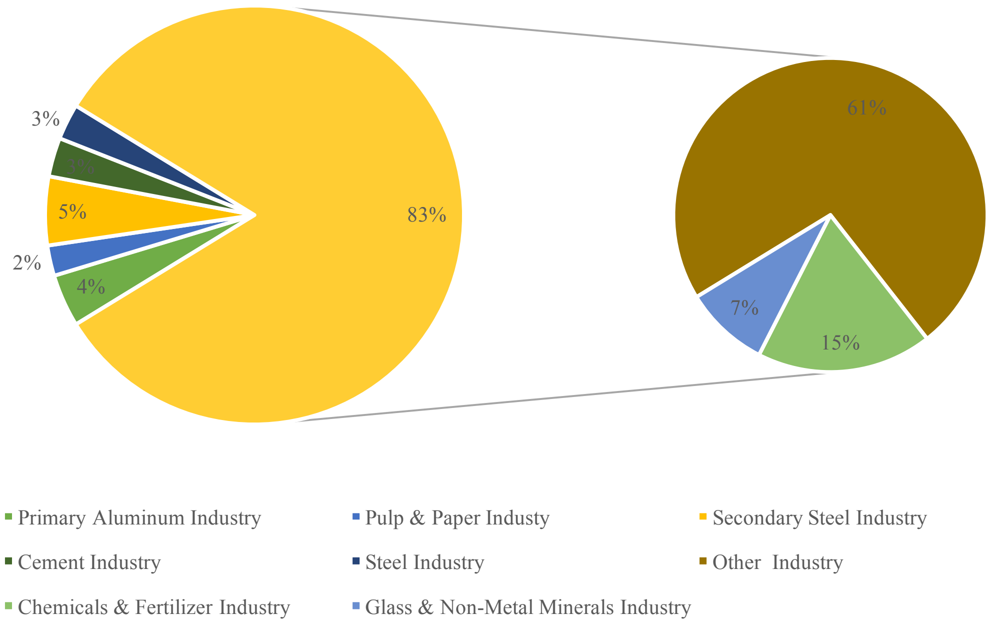


Figure 6.5. Natural gas consumptions under BAU_BM (PJ).

Industry sector also consumes hard coal significantly. 2012 consumption was 294PJ and is projected to reach 1343PJ in 2052. Iron and steel production uses coal heavily, and this is the main reason for this increase. 55.7% of the coal consumption is done by this industry. Another energy intensive sector is cement, and this sector takes 28.6% of the total coal consumption. Details about industry sector natural gas usage are given in Table 6.5.

"Other industry" group which consists of automotive, pharmacy, etc. consumes the most natural gas and is followed by Chemicals and Fertilizers sector. This sector, in particular, uses most of the energy to meet the process heat demand. Under BAU scenario condition, the average efficiency is expected to increase by 12%. Another important natural gas user is Glass and Non-Metal Minerals Industry. In 2012, consumption level was 36PJ, and it is expected to reach 122PJ in 2052.

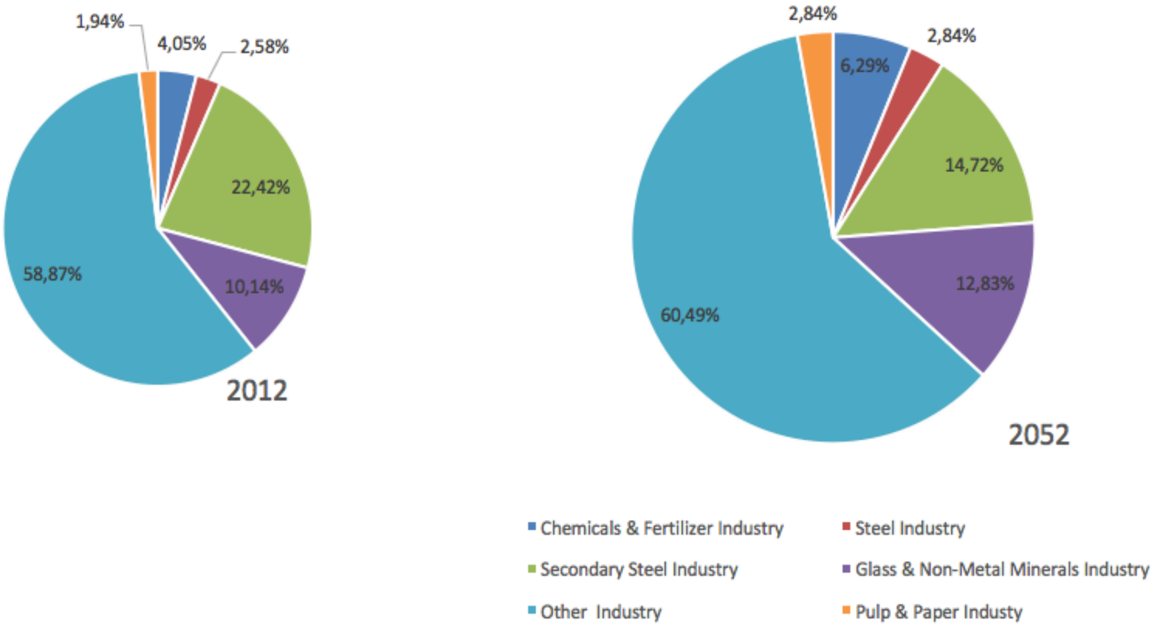


Figure 6.6. Electricity consumptions under BAU_BM (PJ).

Another input to the industry sector is electricity. 81% of the total electricity consumption at base year is secondary steel production and other sectors. They are followed by Glass and Non-Metal Minerals by 10.14%. In secondary steel industry, most of the electricity consumption is for process heat (in 2012, electricity consumption for secondary steel process heat was 45.7PK, electricity consumption for machine drive was 28.28PJ, these levels are expected to be 168.21PJ and 18.87 in 2052 respectively).

In other industries, machines and electrical equipment within the facility uses electricity. As usage values of sectors are calculated according to their production types and quantities, consumption rates vary a lot during the analysis period. Secondary steel share decreases from 22.42% to 14.72%, while Glass and Non-Metal Minerals become a more electricity intensive sector.

6.1.4. Transport Sector

Transportation activity is expected to grow significantly in the next 40 years. It is expected to reach 3283 (PJ) by 2050 whereas this value equals to 3279 in BUEMS_TR. Numbers reveal that electricity usage hits approximately 5,3PJ, but when the consumer technologies are investigated, this increase appears to be resulted heavily from rail transportation. For road transport, gasoline takes the lead. The penetration of alternative technologies, such as electric battery– and hydrogen–powered vehicles are expensive in BAU scenario. Foregone conclusion is that, diesel and gasoline usage are still popular and take the lion share with 57 % and 21% respectively.

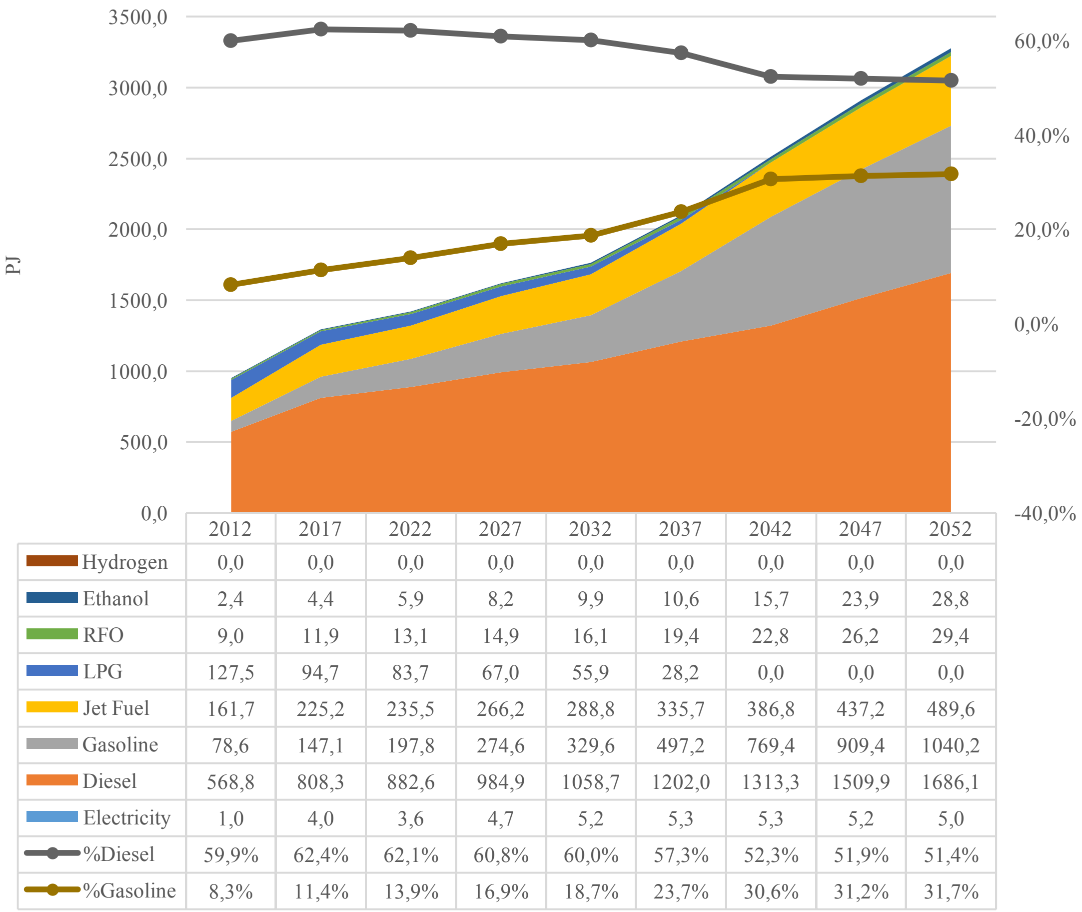
As mentioned before, the demands are modeled separately according to basic transportation types (air transport, road transport, rail transport and maritime transport). These main topics are investigated under sub-consumption demands. In BAU scenario, electricity is completely consumed by rail transport. In 2012, electricity consumption for passenger rail transport was 0.482PJ, and is forecasted to reach 2.46PJ in 2052. In rail freight transport, with track electrification, the consumption level is expected to reach 4.92PJ.

The major fuel type transportation sector uses is diesel with a share of 57.55%. The distribution of diesel usage with respect to sub-topics are presented in Figure 6.7. Diesel consumption of TR sector was 6PJ in 2012 and is expected to show a 2.5 times increase to reach 14.3PJ in 2052. Diesel consumption by bus transport was 27.3PJ in 2012, and is forecasted to reach 30PJ in 2032, and 45.4PJ in 2052.

Diesel is predominantly consumed by light-duty vehicles and passenger cars. For passenger cars, BAU scenario assumes that diesel will continue to be a major selection as the initial investment costs for alternative fuel vehicles will be high.

Gasoline consumption is done by passenger cars and LGV’s. Diesel consumption of other transport classes (tractors, work machines, and unclassified transport types) is expected to rise from 141PJ to 461PJ at the end of the analysis period.

Maritime transport will continue to use its existing fleet that uses only fuel oil until 2018, after this year, it will shift to fuel oil inject which is a higher efficient technology. The whole fuel oil consumption of the sector is done by maritime transport.

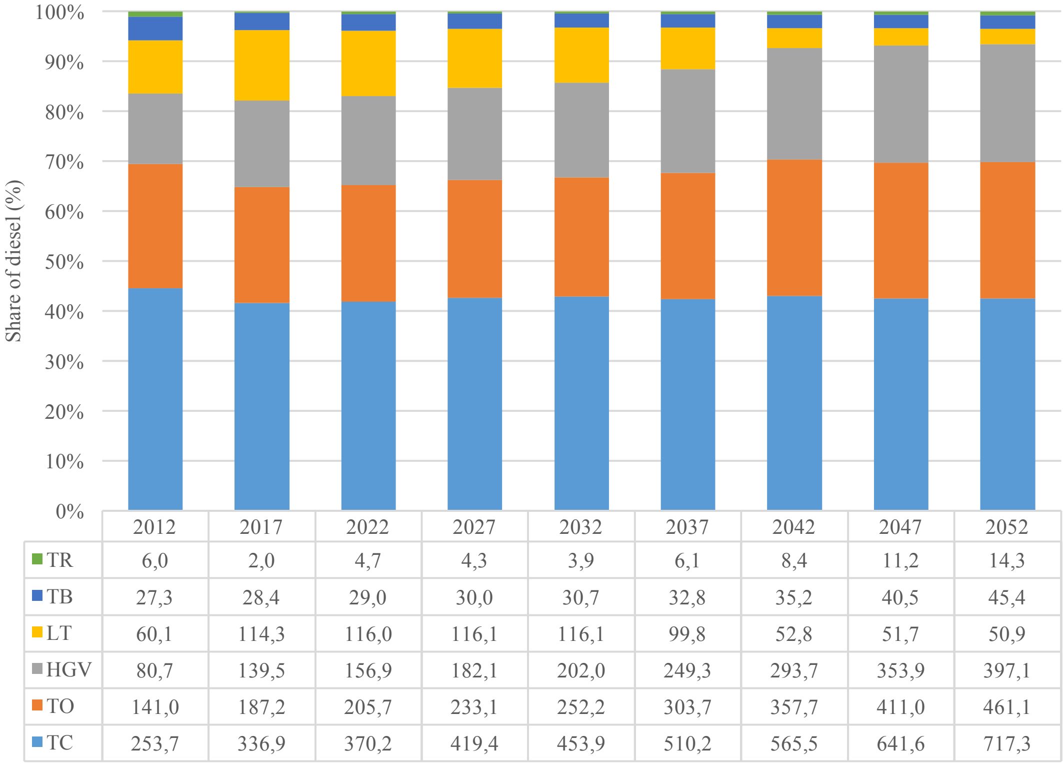


	2012	2017	2022	2027	2032	2037	2042	2047	2052
Hydrogen	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ethanol	2,4	4,4	5,9	8,2	9,9	10,6	15,7	23,9	28,8
RFO	9,0	11,9	13,1	14,9	16,1	19,4	22,8	26,2	29,4
LPG	127,5	94,7	83,7	67,0	55,9	28,2	0,0	0,0	0,0
Jet Fuel	161,7	225,2	235,5	266,2	288,8	335,7	386,8	437,2	489,6
Gasoline	78,6	147,1	197,8	274,6	329,6	497,2	769,4	909,4	1040,2
Diesel	568,8	808,3	882,6	984,9	1058,7	1202,0	1313,3	1509,9	1686,1
Electricity	1,0	4,0	3,6	4,7	5,2	5,3	5,3	5,2	5,0
%Diesel	59,9%	62,4%	62,1%	60,8%	60,0%	57,3%	52,3%	51,9%	51,4%
%Gasoline	8,3%	11,4%	13,9%	16,9%	18,7%	23,7%	30,6%	31,2%	31,7%

Figure 6.7. Transport sector fuel consumptions under BAU_BM (PJ).

In order to benchmark transport sector in BUEMS_TR model, TIMES_TR model results are given in Figure C.2. When values are examined, diesel consumption is observed to be slightly less in TIMES_TR (values vary from 48.4% to 61.8%). In BUEMS_TR diesel consumption is between 51.4% and 62.4%.

On the other hand, gasoline consumption is higher in TIMES_TR. BUEMS_TR forecasts a maximum level of 1040PJ, while TIMES_TR projects that value as 1094PJ.



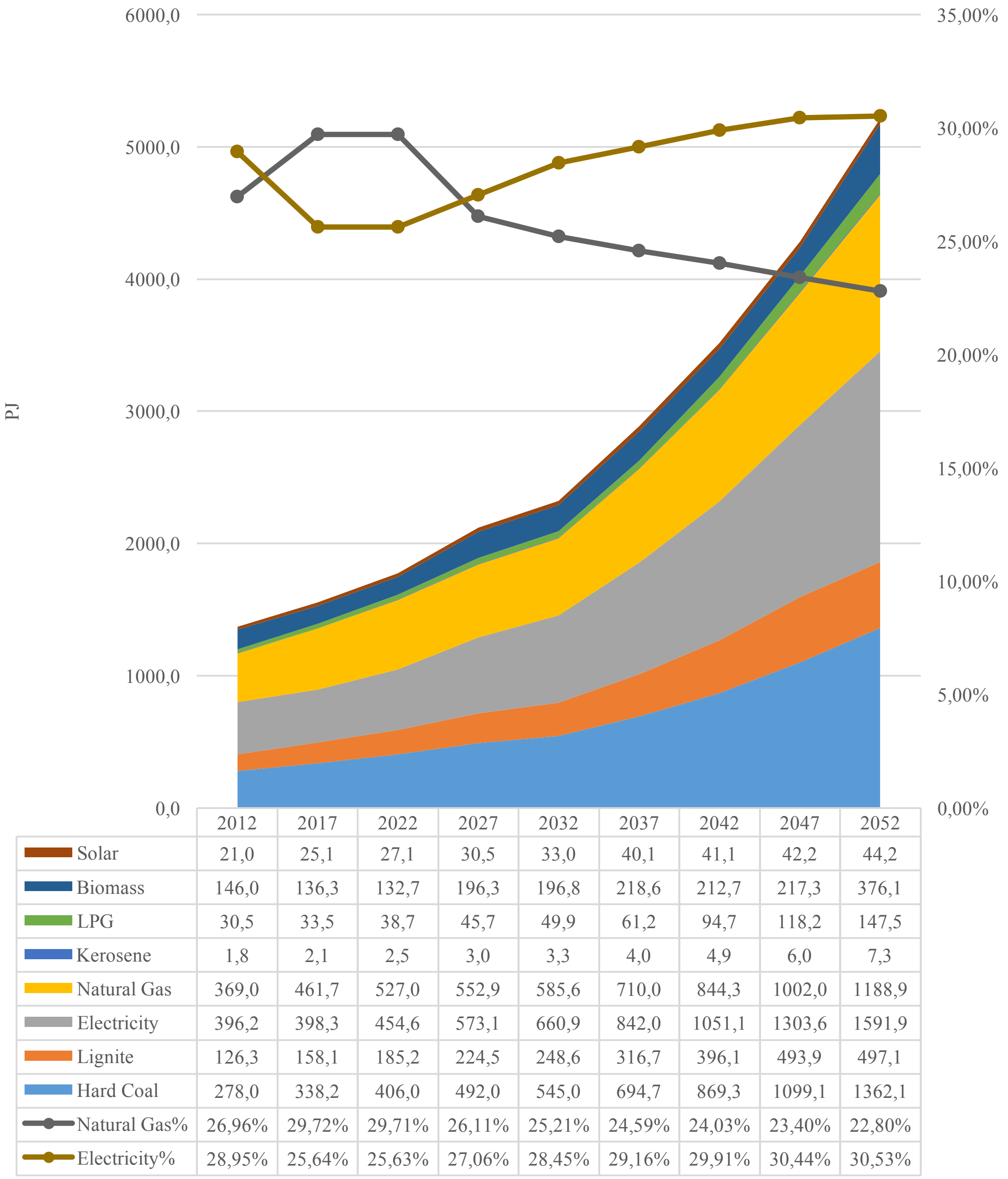
	2012	2017	2022	2027	2032	2037	2042	2047	2052
🟩 TR	6,0	2,0	4,7	4,3	3,9	6,1	8,4	11,2	14,3
🟦 TB	27,3	28,4	29,0	30,0	30,7	32,8	35,2	40,5	45,4
🟨 LT	60,1	114,3	116,0	116,1	116,1	99,8	52,8	51,7	50,9
⬜ HGV	80,7	139,5	156,9	182,1	202,0	249,3	293,7	353,9	397,1
🟧 TO	141,0	187,2	205,7	233,1	252,2	303,7	357,7	411,0	461,1
🟦 TC	253,7	336,9	370,2	419,4	453,9	510,2	565,5	641,6	717,3

Figure 6.8. Transport sector shares of diesel consumption under BAU_BM (%).

6.1.5. Residential and Commercial Sector

The residential and commercial sectors include all homes and commercial businesses (excluding agricultural and industrial activities) requiring large amounts of energy for heating, cooling, lighting, and other functions. Residential and commercial sector is modelled with detailed structure of energy demand technologies (257 different technologies are identified) in order to represent all of the above mentioned demand groups.

In 2012, 35.4% of total energy consumption was attributable to the residential and commercial sector and this demand is expected to be doubled by 2052 as presented in Figure 6.9. The fuel consumption structure remains stable for electricity during the projection period. The share of electricity within the gross energy consumption equals 30% by 2032 and expected to grow faster afterwards.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Solar	21,0	25,1	27,1	30,5	33,0	40,1	41,1	42,2	44,2
Biomass	146,0	136,3	132,7	196,3	196,8	218,6	212,7	217,3	376,1
LPG	30,5	33,5	38,7	45,7	49,9	61,2	94,7	118,2	147,5
Kerosene	1,8	2,1	2,5	3,0	3,3	4,0	4,9	6,0	7,3
Natural Gas	369,0	461,7	527,0	552,9	585,6	710,0	844,3	1002,0	1188,9
Electricity	396,2	398,3	454,6	573,1	660,9	842,0	1051,1	1303,6	1591,9
Lignite	126,3	158,1	185,2	224,5	248,6	316,7	396,1	493,9	497,1
Hard Coal	278,0	338,2	406,0	492,0	545,0	694,7	869,3	1099,1	1362,1
Natural Gas%	26,96%	29,72%	29,71%	26,11%	25,21%	24,59%	24,03%	23,40%	22,80%
Electricity%	28,95%	25,64%	25,63%	27,06%	28,45%	29,16%	29,91%	30,44%	30,53%

Figure 6.9. RES and COM sector fuel consumptions under BAU_BM (PJ).

Figure 6.10 shows which residential and commercial electricity consumption is for meeting which demand type. The highest electricity consuming item is refrigerant demand. In 2012, it corresponded to 28% of all electricity consumption, the value of this is expected to reach 119TWh in 2052. Another important consumption category is under "appliances" which includes all residential and commercial appliances that cannot be categorized in other topics such as, ovens, TV's, computers, etc. This topic had 21,47TWh consumption in the base year and is expected to reach 145TWh in 2052.

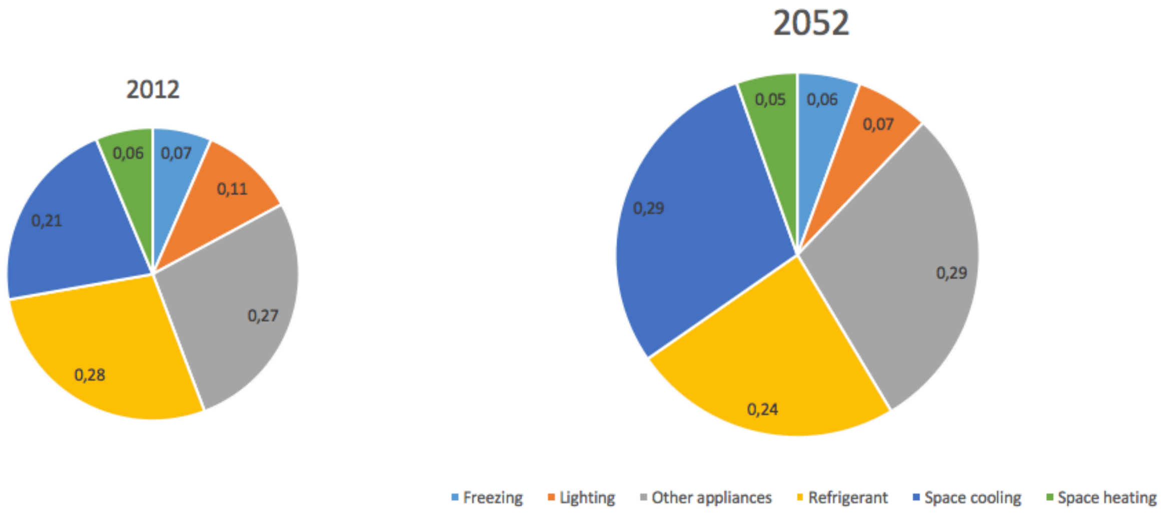


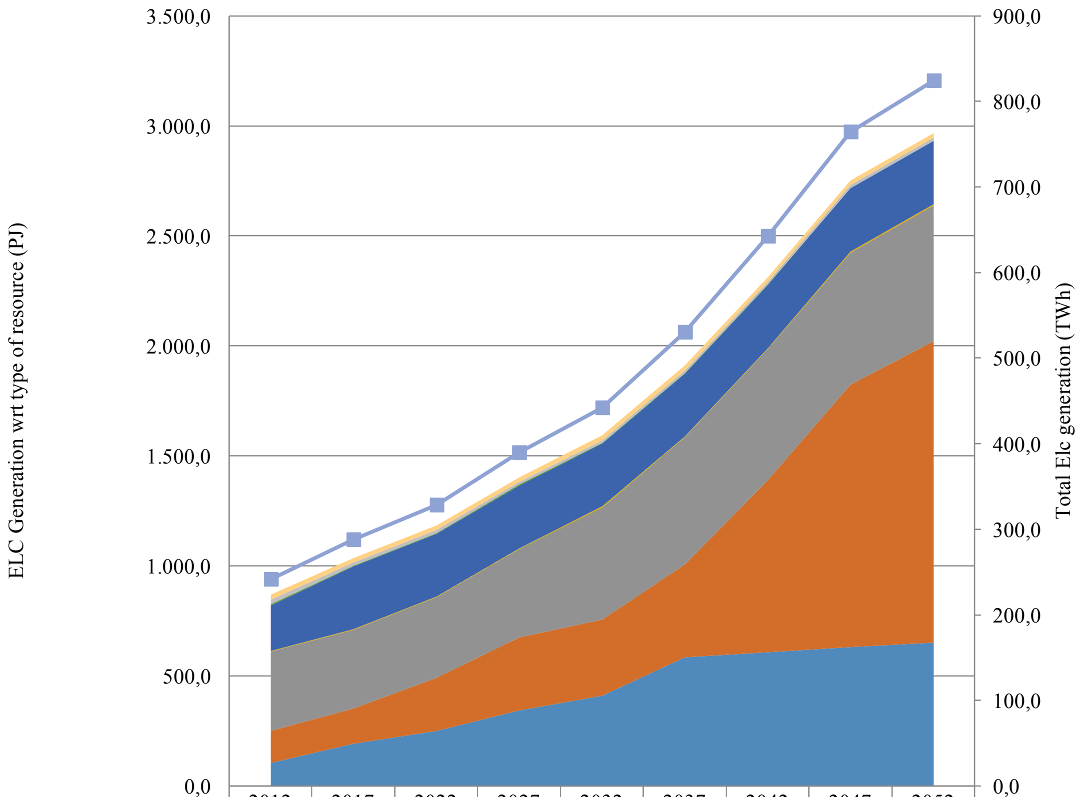
Figure 6.10. RES and COM sector fuel consumptions under BAU_BM (PJ).

Another important energy consumption item is space cooling. The space cooling demand of 17TWh in the base year 2012, is expected to increase constantly and reach 29% of total electricity consumption in 2052.

TIMES_TR model results are given in Figure C.3 in Appendix C. Electricity consumption is lower with respect to BUEMS_TR model. Electricity consumption of year 2032 is observed to be 596,4 in TIMES_TR, 660,9 in BUEMS_TR. It is also observed that natural gas consumption reaches 1201,2PJ in TIMES_TR which is higher than that of BUEMS_TR.

6.1.6. Power Sector

In BAU scenario, electricity generation increases by approximately 3 times during 2012-2052 to meet continuously increasing electricity demand in the end-use sectors. Turkish electricity sector heavily relies on coal (39%, including hard coal and lignite), hydroelectric power usage (with 11% of total consumption), and natural gas (44%) by the year 2012. The share of coal is expected to hit 69 % of total electricity generation at the end of the projection period. The amount of electricity produced from renewable energy in Turkey is expected to remain stable for geothermal, solar and hydro, whereas wind power gradually decreases to 12.2 (PJ).



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Electricity-IMP	21,0	21,0	21,0	21,0	21,0	21,0	21,0	21,0	21,0
Wind	21,5	14,3	12,5	12,5	12,5	12,2	12,2	12,2	12,2
Nuclear	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Solar	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RFO	4,8	5,0	4,5	4,1	3,3	2,5	1,7	0,8	0,0
Hydro	208,0	282,7	283,3	285,5	285,9	286,1	287,6	289,0	290,4
Geothermal	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Natural Gas	359,7	358,8	365,4	401,9	509,4	577,7	595,6	601,3	617,6
Lignite	146,3	158,2	241,3	330,3	347,4	421,9	783,0	1.191,3	1.370,0
Hard Coal	103,5	192,8	251,4	343,4	409,3	584,5	608,0	631,4	651,3
Total	241,2	287,9	328,6	389,6	442,4	530,5	642,4	764,1	824,0

Figure 6.11. Electricity generation wrt the source of energy (PJ).

Determining emissions from electrical energy production on energy resource type is important for determining energy policies that will be followed to decrease greenhouse gas emissions. Fuel based electricity productions are given in Figure 6.11 in detail. It would not be wrong to consider four main energy resource classes in Power Sector. Hard coal and lignite classes which are rich in local reserves; natural gas; and finally renewables class that include hydropower, solar, geothermal, and the wind. The shares of usages of these four main classes in electricity production are given in Figure 6.12.

When we look at the base year production numbers, we see that the major energy consumption is natural gas (approx. 100TWh), followed by lignite (~69,4 TWh), and hard coal. Under renewable class, hydropower solely provided 57,8 TWh worth of electricity production. In 2052 share of natural gas is expected to decrease to 21% from its current 43% level. Although the share of natural gas will reduce, its total production will increase from 100TWh to 172TWh.

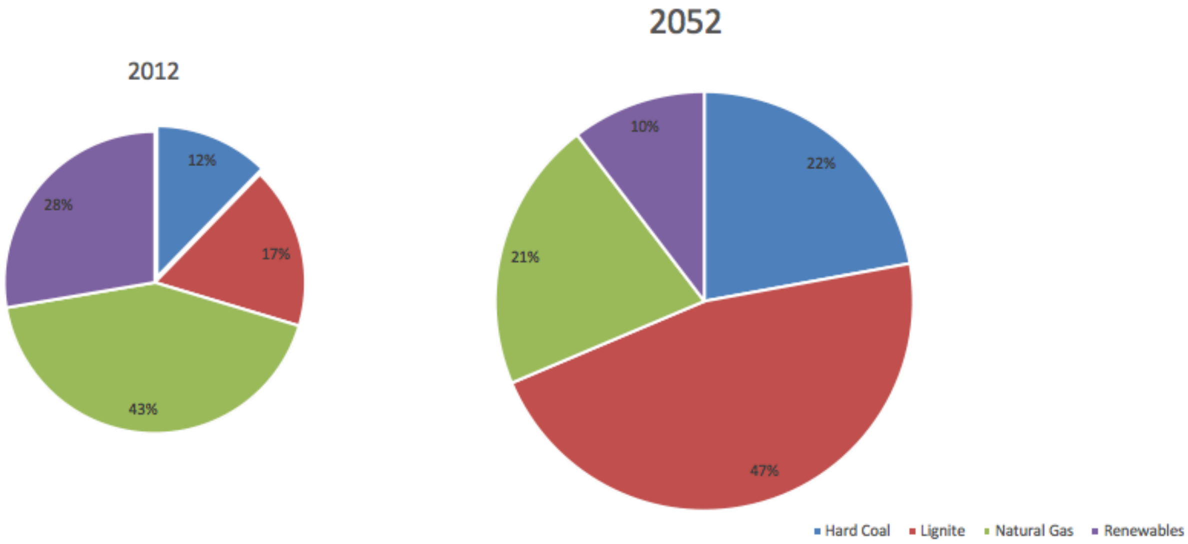


Figure 6.12. Share of electricity generation by source (%).

Figure C.4 in Appendix C shows power sector fuel consumptions calculated by TIMES_TR model in order to compare BUEMS_TR model. According to TIMES_TR model results, lignite usage is higher, while hard coal consumption is lower. When difference in total electricity production is analyzed, BUEMS_TR model forecasts 390TWh and 824TWh for 2027 and 2052 years respectively, while values for TIMES_TR model are 374TWh and 893 TWh.

6.1.7. Emissions

In this section, how emissions are shaped under the reference scenario is shown[2]. Main reason for greenhouse gas emissions in Turkey is energy sector as fossil fuels are burned for

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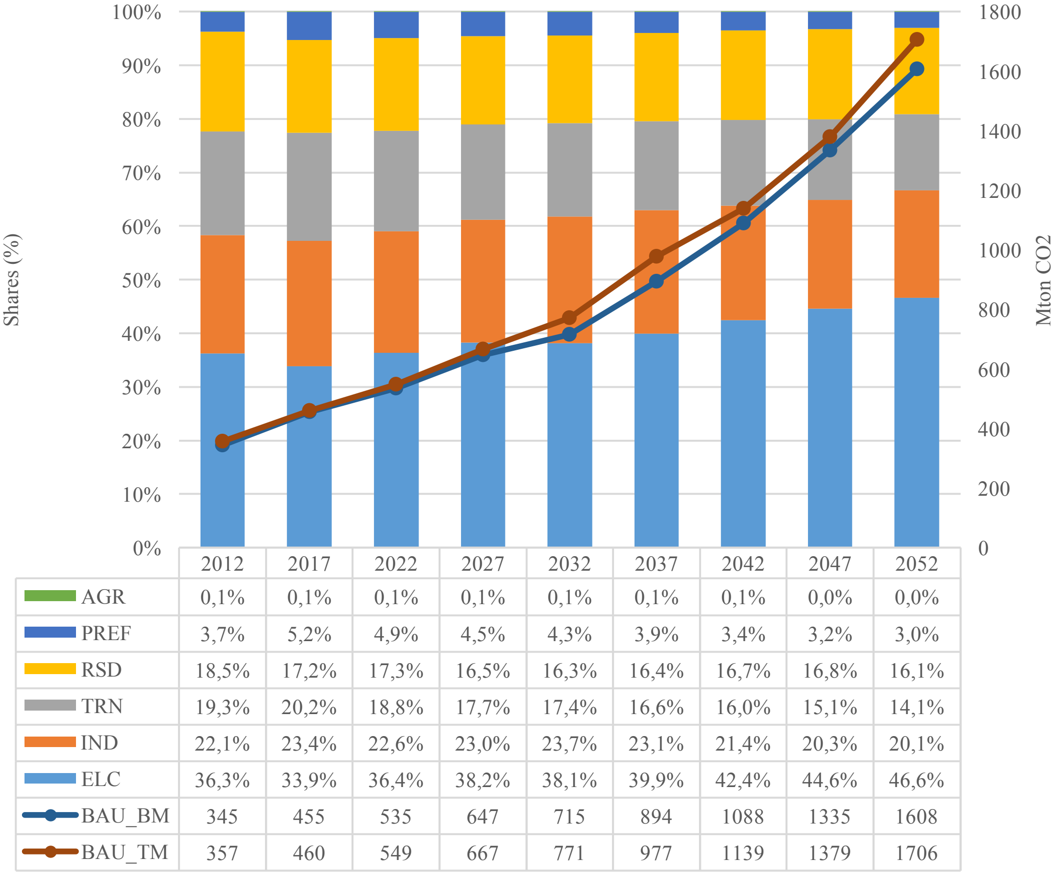
[2] Process emissions are not included into the BUEMS_TR model

this. For the base year, Power Sector was the reason for 36,3% of total emissions, and will continue to be the main reason with 38,1% share in 2032 and 46,6% share in 2052 as illustrated in Figure 6.13.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
AGR	0,1%	0,1%	0,1%	0,1%	0,1%	0,1%	0,1%	0,0%	0,0%
PREF	3,7%	5,2%	4,9%	4,5%	4,3%	3,9%	3,4%	3,2%	3,0%
RSD	18,5%	17,2%	17,3%	16,5%	16,3%	16,4%	16,7%	16,8%	16,1%
TRN	19,3%	20,2%	18,8%	17,7%	17,4%	16,6%	16,0%	15,1%	14,1%
IND	22,1%	23,4%	22,6%	23,0%	23,7%	23,1%	21,4%	20,3%	20,1%
ELC	36,3%	33,9%	36,4%	38,2%	38,1%	39,9%	42,4%	44,6%	46,6%
BAU_BM	345	455	535	647	715	894	1088	1335	1608
BAU_TM	357	460	549	667	771	977	1139	1379	1706

Figure 6.13. BUEMS_TR emissions (%).

The second important sector is industry sector, with a 22,2% average share during the 2012-2052 period. With a total emission value of 1743Mton CO_2, considering emission reducing precautions in this sector is of utmost importance. The main reasons for emissions in this sector are steel and cement production. High coal consumption in these sectors results in high emissions.

Calculations show that there will be an increase in all greenhouse gas emissions, especially CO_2 emissions due to increasing fuel consumptions. In transport sector, it is known that the main emission reason is diesel and gasoline consumption, hence the road transport.

As diesel usage in rail transport decreases, the fuel used in rail transport decreases. Consequently, the emission values decrease. This does not mean a decrease in general usage of rail transport. Especially in passenger rail transport, there is a certain shift to electric locomotives. Diesel engine locomotives are now mainly used in freight transport. This shift is also a reason for the reduction in total emissions.

When we evaluate how emissions shape under BAU scenario, it is expected that emission values will increase from 345 Mton CO_2 in 2012 excluding process emissions (TIMES_TR model provides this value as 357 Mton CO_2) to 715 Mton CO_2 in 2032and finally to 1608 Mton CO_2 in 2052 (1883 Mton CO_2 when process emissions are included). The total difference between TIMES_TR model and BUEMS_TR model for BAU scenario is expected to be 381 Mton CO_2.

6.1.8. Costs

Energy projection models provide information about energy demand forecasts, production capacity increases, changes in technology or alternative fuel selection processes. Investment decisions are made based on the goal of reaching minimum costs, considering this information. In this section, Business-as-Usual (BAU) scenario is investigated where all future technology investments and fuel consumption decisions are given under the current conditions, trends, and limitations.

Table 6.6. Total system cost under BAU_BM scenario (2012 Million US $).

	2012	2017	2022	2027	2032	2037	2042	2047	2052
Activity	7924	8561	9526	10740	11530	13533	15082	17068	18962
Fuel flow	50569	45375	51277	60308	66796	81068	96715	113417	168517
Fix O.M.	441243	607168	672533	769544	836933	1050120	1247293	1378834	1505122
Investment	717961	1226806	1424386	1716746	1918212	2770609	3559208	3950127	4363980
Total	1217698	1887911	2157722	2557338	2833471	3915330	4918299	5459447	6056581

Breakdown of costs result in four main topics: activity, fuel flow, fix operating and maintenance cost. Investment costs constitute approximately 60% of total costs as presented in Table 6.6. It is forecasted that the total cost will double by 2032, and exceed 6 trillion $ by 2052, which is approximately five times its value in 2012. TIMES_TR model provides cost values that is higher than BUEMS_TR model. TIMES_TR predicts that total system cost will be equal to 1221917 Million US $ for the base year and 6498796 for 2052.

6.2. Carbon Tax Scenario Results

Policies to be used for decreasing greenhouse gasses include economic and fiscal tools as well as having a broad spectrum of activities from voluntary agreements between shareholders of the sector to arranging programs in order to raise awareness among people about energy saving.

The term of “tradable permits” yields the concept of maximum available emission levels, and the notion of permitting emissions to a certain degree came into existence. To that end, selling some percentage of the allowed carbon emissions is accepted as an efficient policy tool (Montgomer, 1972).

As one of the most important control mechanisms against global warming and carbon emissions, Kyoto protocol in 1997 aimed at organizing upper emission limit and its trading system (Zhang and Xu, 2013). After that, European Union Emission Trading System (EU-ETS) was announced in 2005 and by creating the biggest carbon emission market of the present day, a crucial step toward fighting against climate change is taken.

Emission reduction credit system and cap and trade system comprise the two basic policy tools (Cicek and Cicek, 2012). These two policy tools are essentially aiming at keeping the emissions increase at a certain level by allowing emissions within ecologically sustainable boundaries and by making transaction of emission permits possible.

Another commercial permit system is the “Credit Systems” and it includes three main titles namely Clean Development Mechanism, Joint Implementation Programs, and Carbon Balancing.

If CDM and Annex-1 countries create projects to transfer their advanced technologies to developing countries they will be helping countries which are not listed in any of the annexes to reduce their emissions and they will gain Certification of Emissions Reduction

(CER) and that credit amount can be deduced from their emission reduction commitments (Karakaya, 2008).

Another project based flexible emission reduction method regulated by Kyoto protocol is “Joint Implementation” programs. By implementing JI program, Emission Reduction Unit-ERU can be gained if a project between two annex-1 countries manages to reduce emissions (Bretone, 2005).

Carbon balancing is based on volunteering. A firm calculates the quantity of the greenhouse gas emissions resulting from its operations and then it invests in a project which will reduce emissions as much as the firm's ecological footprint and/or the firm purchases carbon certificate at the same amount of the emissions that it caused.

Along with market-based policy tools, tools for advancing research and development activities, raising public awareness by organizing workshops and other activities of volunteering organizations, taxes and subsidies directly introduced to the market by the state are also used.

Carbon taxes are levied by many countries as a policy tool to diminish the volume of the emissions. Shortly it is defined as a tax on carbon emissions emerging from the consumption of fossil fuels (Conte and Kotchen, 2009). The purpose of the carbon tax is to promote the use of clean technology and fuel options and to reduce the use of fossil fuels and the negative exteriority caused by it. The carbon tax is first applied in Finland (1990) and Scandinavian countries (Netherlands-1990, Norway-1991, Sweden-1991, etc.). Emission tax per ton varies widely among countries, and it fluctuates between 15.93 dollars in Norway to 104.83 dollars in Sweden (Sumner *et al.*, 2009).

As previously stated, the extent of carbon pricing schemes and the level of CO_2 prices vary across countries. To that end, four different carbon pricing scenarios are also investigated by levying the above-mentioned tax values.

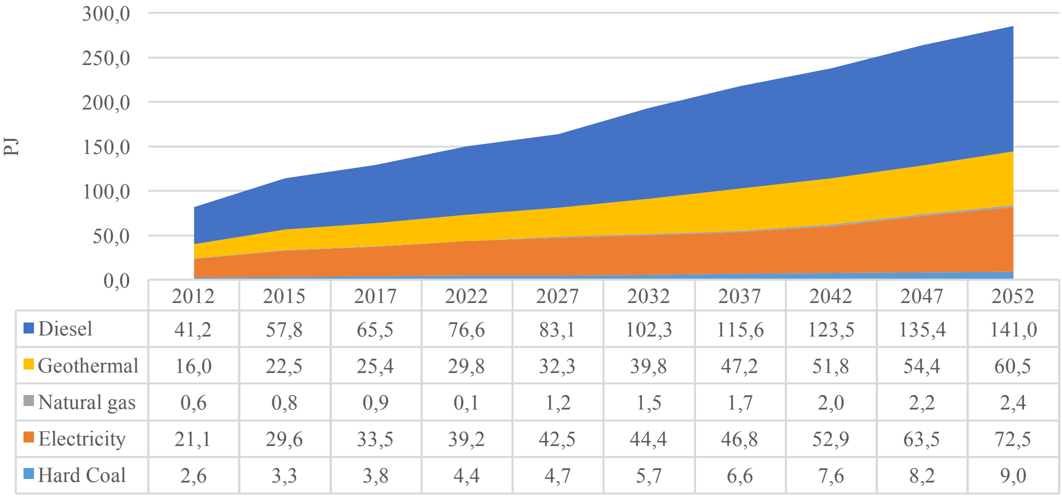
Among various mitigation measures, considering the advantages and the implementation feasibility of the policy itself, this section focuses on the effects of levying carbon tax on different sectors from the aspect of changes in fuel consumptions. Another motivation is that, setting a carbon price is stated as the most significant opportunity (Leonhardt, 2010).

Under the assumption that all of the pre-defined constraints for BAU scenario is valid, carbon tax is introduced into the model to examine how much carbon emissions from Turkey energy system would decrease in response to a change in carbon price.

In order to reveal the impacts of carbon tax on national scale, four level carbon tax has been carried out. \$10/tons of $CO_{2,}$ \$20/tons of CO_2, \$30/tons of CO_2 and \$50/tons of CO_2 options are examined as separate scenarios. In this section the outcomes associated with the carbon tax scenarios are presented on sectorial basis first, and followed by general discussion on cost and emission figures.

6.2.1. Agriculture Sector

Rising energy prices and changing energy and environmental policies have altered the relationship between the agriculture and energy sectors. Changes in energy prices can affect all facets of the economy, including the agriculture sector. In carbon tax scenario, energy prices have changed within the model by levying a tax on it.



	2012	2015	2017	2022	2027	2032	2037	2042	2047	2052
Diesel	41,2	57,8	65,5	76,6	83,1	102,3	115,6	123,5	135,4	141,0
Geothermal	16,0	22,5	25,4	29,8	32,3	39,8	47,2	51,8	54,4	60,5
Natural gas	0,6	0,8	0,9	0,1	1,2	1,5	1,7	2,0	2,2	2,4
Electricity	21,1	29,6	33,5	39,2	42,5	44,4	46,8	52,9	63,5	72,5
Hard Coal	2,6	3,3	3,8	4,4	4,7	5,7	6,6	7,6	8,2	9,0

Figure 6.14. Agriculture sector fuel consumptions under CO2_50_BM (PJ).

The fuel consumption structure remains stable for natural gas, hard coal and geothermal during the projection period as presented in Figure 6.14. The share of electricity within the gross energy consumption equals 30%, for the period 2023-2030 and diminishes throughout the 2030-2050 period. When investigating the fuel usage values, numbers reveal that although the fuel consumption is same due to the efficiency increase with respect to the BAU scenario on the average the emissions decreased by 6.25% regardless of the rate of tax. The consumption structure remains stable for diesel till 2032.

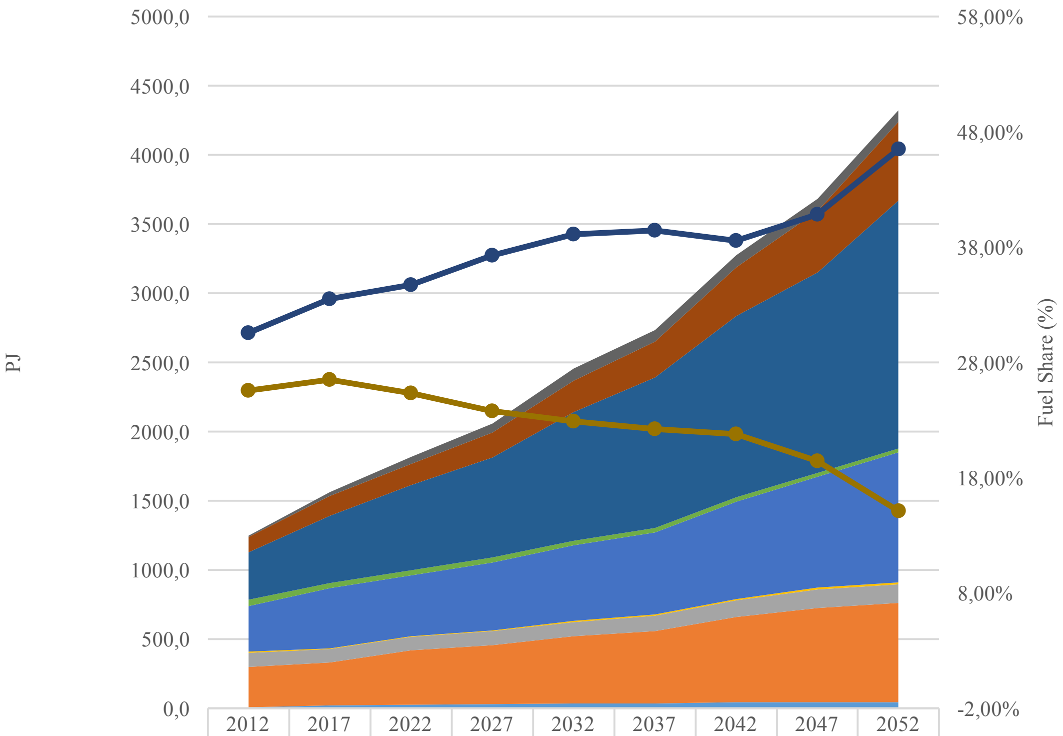
6.2.2. Industry Sector

This section measures the expected environmental benefits of industry sector from fuel switching in response to a range of carbon prices presented as tax. The fuel consumption values for each of scenarios are presented in Figure 6.15.

Hard coal consumption continued to decline in CO2_20_BM and C02_30_BM scenarios up to the year 2042 and has remained stable afterwards with respect to the BAU scenario. Due to increased substitution prices (especially for Natural gas and electricity), no additional cost effective reduction of coal is possible under aforementioned carbon tax scenarios. Under $50 carbon tax scenario, model achieves to reduce coal throughout the planning horizon. Although coal constitutes approximately %25 of total fuel consumptions this value diminishes and drop below 15%. It is worth mentioning that in 2052 hard coal consumption is anticipated to hit 1342PJ in BAU scenario whereas it is predicted to be 675PJ under the strictest emission tax scenario.

Lignite consumption has also decreased in CO2_50_BM and scenario compared to BAU. The mitigation of lignite is as aggressive as coal. Total reduction is expected to be 41PJ (equivalent to %3 of total consumption within the period of 2012-2052). Additionally, it is wort mentioning that lignite consumption under CO2_10_BM and CO2_20_BM remain unchanged with respect to reference case. Under low emission tax case, model promotes hard coal consumption instead of lignite where as high emission case, natural gas becomes prominent as a substitute of hard coal.

Another point of interest is that, technologies (Solar, geothermal etc.) require limited resources and high-priced investment are not preferred, whereas technologies that consume electricity and natural gas are more eligible comparing to them.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Solar	10,8	31,3	49,7	63,7	87,4	87,4	87,4	87,4	85,2
Petrocoke	111,5	141,6	153,9	180,7	227,9	259,5	349,6	447,2	566,6
Natural gas	341,3	485,1	615,9	723,1	928,2	1086,3	1313,1	1448,3	1794,5
Geothermal	44,0	38,7	36,8	35,8	34,5	34,0	31,8	29,9	29,1
Electricity	330,0	436,6	440,0	490,2	546,0	590,3	701,6	799,1	937,7
Oil	9,4	3,6	5,0	6,8	6,5	8,3	8,3	12,1	13,1
Lignite	100,7	95,1	93,5	103,2	104,7	113,2	121,8	135,6	136,5
Hard Coal	293,7	310,7	394,2	424,7	487,1	521,7	617,8	682,0	718,8
Asfaltite	6,3	21,9	26,2	28,8	32,6	35,3	42,5	42,5	41,2
Coal%	25,55%	26,51%	25,34%	23,78%	22,86%	22,21%	21,76%	19,46%	15,10%
Natural gas%	30,54%	33,48%	34,71%	37,29%	39,12%	39,44%	38,54%	40,83%	46,53%

Figure 6.15. Industry sector fuel consumptions under CO2_50_BM (PJ).

Additionally, carbon tax provides incentives for fuel switching in industry sector. Briefly, higher carbon tax makes hard coal and lignite consumed technologies less competitive than alternatives that utilized natural gas and electricity as in Figure 6.15.

To compare TIMES_TR and BUEMS_TR models, Figure C.5 shows how industry sector is shaped under CO2_50_TM scenario. When natural gas consumption is analyzed, BUEMS_TR model forecasts that consumption will reach 1795PJ in 2052. This value is 1814PJ in TIMES_TR model. Hard coal consumption forecasts for 2052 are 682PJ in TIMES_TR model, 718PJ in BUEMS_TR model.

Under decarbonisation pathways, the industry sector is one of the key sectors. However, it is stressed that in model experiments that this sector does not respond to carbon tax sufficiently under \$10, \$20and \$30 case.

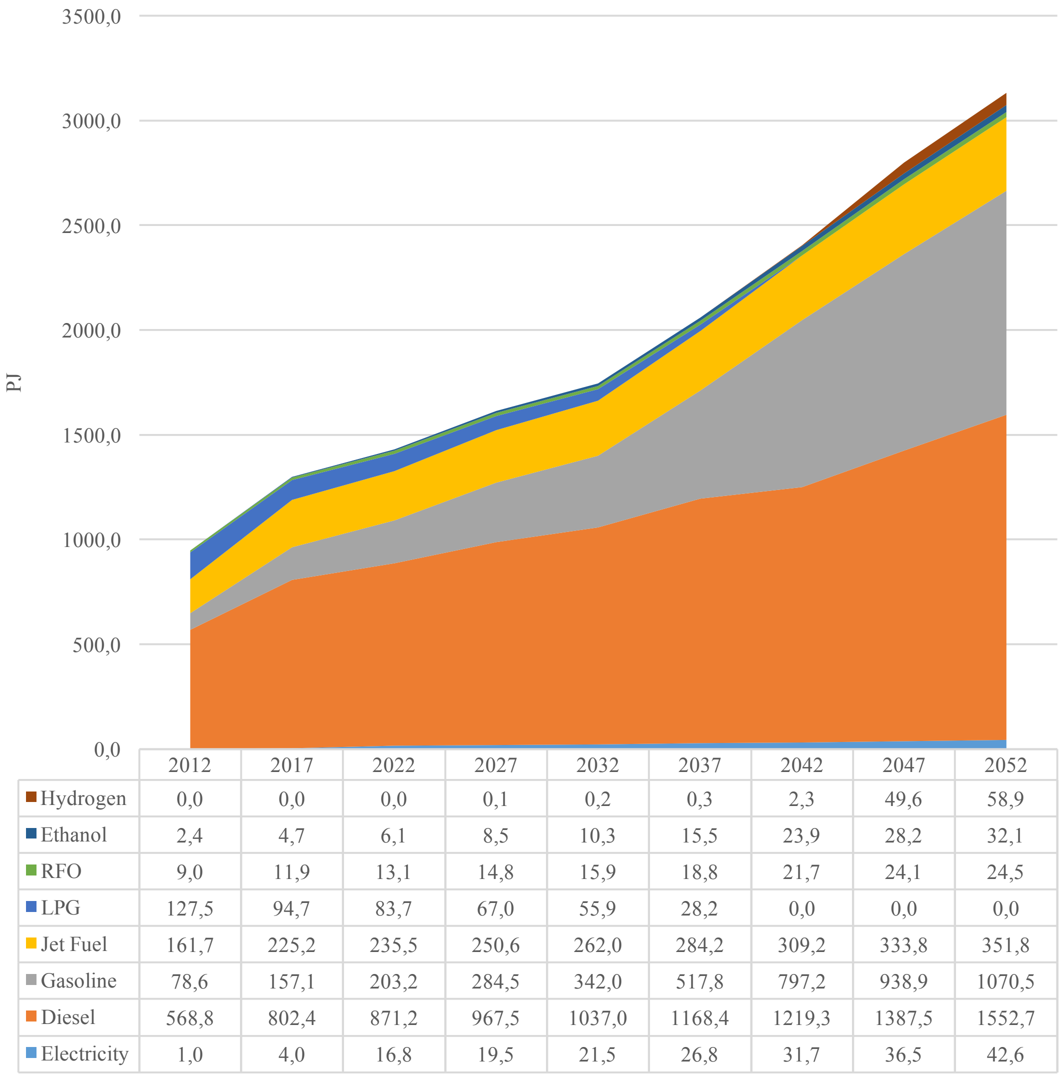
Moreover, process emissions that counted under greenhouse gas emissions resulted from industry are not able to alternate since they are calculated with respect to end use production amounts.

6.2.3. Transport Sector

Transportation activity is expected to grow significantly of the following years and to reach 3129 (PJ) by 2052 in BAU scenario. In Figure 6.16, the structure of this expansion is displayed in terms of fuel types for CO2_50_BM carbon emission scenarios. The numbers reveal that gasoline usage gets the lion share in each of four emission scenario and when the consumer technologies are investigated, this increase appears to be resulted heavily from road transportation.

The transport sector is decarbonized via a range of technology options by mode, first by electricity (hybrid plug-in) for road transport when carbon tax imposed which is higher than \$30per ton of CO_2. The consumption of electricity is anticipated to reach its highest value under \$50 emission tax. Although, total electricity consumption in BAU is expected to be 43.80PJ, this value is predicted to reach 204.5PJ.

On the other hand, when air transport is the point in question, model prefers hydrogen consumption rather than jet fuel. Since hydrogen produced by electrolysis, related emission value is lesser than that of jet fuel which makes it desirable.



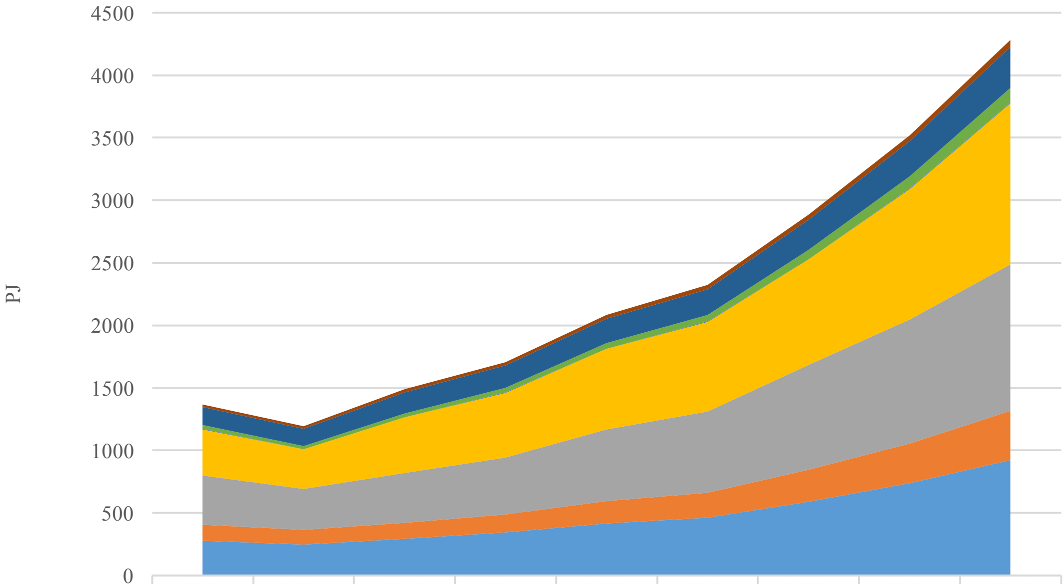
	2012	2017	2022	2027	2032	2037	2042	2047	2052
Hydrogen	0,0	0,0	0,0	0,1	0,2	0,3	2,3	49,6	58,9
Ethanol	2,4	4,7	6,1	8,5	10,3	15,5	23,9	28,2	32,1
RFO	9,0	11,9	13,1	14,8	15,9	18,8	21,7	24,1	24,5
LPG	127,5	94,7	83,7	67,0	55,9	28,2	0,0	0,0	0,0
Jet Fuel	161,7	225,2	235,5	250,6	262,0	284,2	309,2	333,8	351,8
Gasoline	78,6	157,1	203,2	284,5	342,0	517,8	797,2	938,9	1070,5
Diesel	568,8	802,4	871,2	967,5	1037,0	1168,4	1219,3	1387,5	1552,7
Electricity	1,0	4,0	16,8	19,5	21,5	26,8	31,7	36,5	42,6

Figure 6.16. Fuel consumption of transport sector under CO2_50_BM (PJ).

While numerical results will differ by scenario slightly under $10, $20, $30 it is clear that transport sector can only react to emission tax sufficiently when higher emission tax imposed as Figure 6.16 depicts. Although transportation is varied along many dimensions (motor types, efficiency levels, etc.) while investigating in a technology level, for any mode of transport (road, rail, maritime, air) issues will be the same and system almost shows no response under low carbon price. Low-cost emission reduction potential of the model with the exception of transport sector can be accounted for unresponsive status of it. TIMES_TR results for $50 emission tax scenario are given in Figure C.6 to show how TIMES_TR and BUEMS_TR model results differ. Total hydrogen consumption is observed to be 111.4PJ, while this value is 90.5PJ for TIMES_TR. Total electricity consumption is equal to 200PJ in BUEMS_TR model. This value is 216PJ in TIMES_TR.

6.2.4. Residential and Commercial Sector

This section examines how a carbon tax is likely to affect emissions from the residential and commercial sector. Since the highest sector response is revealed under CO2_50_BM scenario, fuel consumption values under $50 carbon tax case are depicted in Figure 6.10.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Solar	21	22	25	27	30	33	40	49	59
Biomass	146	137	169	180	196	208	241	280	324
LPG	31	26	33	37	45	50	76	95	118
Kerosene	2	2	2	3	3	3	4	5	6
Natural Gas	369	317	442	518	642	716	840	1047	1289
Electricity	396	322	400	457	572	651	842	991	1171
Lignite	126	121	126	143	178	199	253	317	395
Hard Coal	278	246	294	342	418	463	590	738	921

Figure 6.17. Fuel consumption of residential sector under CO2_50_BM (PJ).

Hard coal and lignite consumptions continued to increase in all scenarios up to the year 2052 and has remained unchanged in CO2_10_BM and CO2_20_BM scenarios. On the other hand, due to their low carbon intensity especially for natural gas and electricity their consumption values are expected to be higher under CO2_30_BM and CO2_50_BM compared to BAU scenario. Although there exists a positive trend in hard coal consumption, total amount is reduced by 14% (equivalent to 876PJ) comparing to BAU consumptions. The share of natural gas within the gross energy consumption equals 30% by 2032 and expected to grow faster afterwards. The absolute increase in the natural gas consumption compared to BAU is anticipated to be 1298PJ.

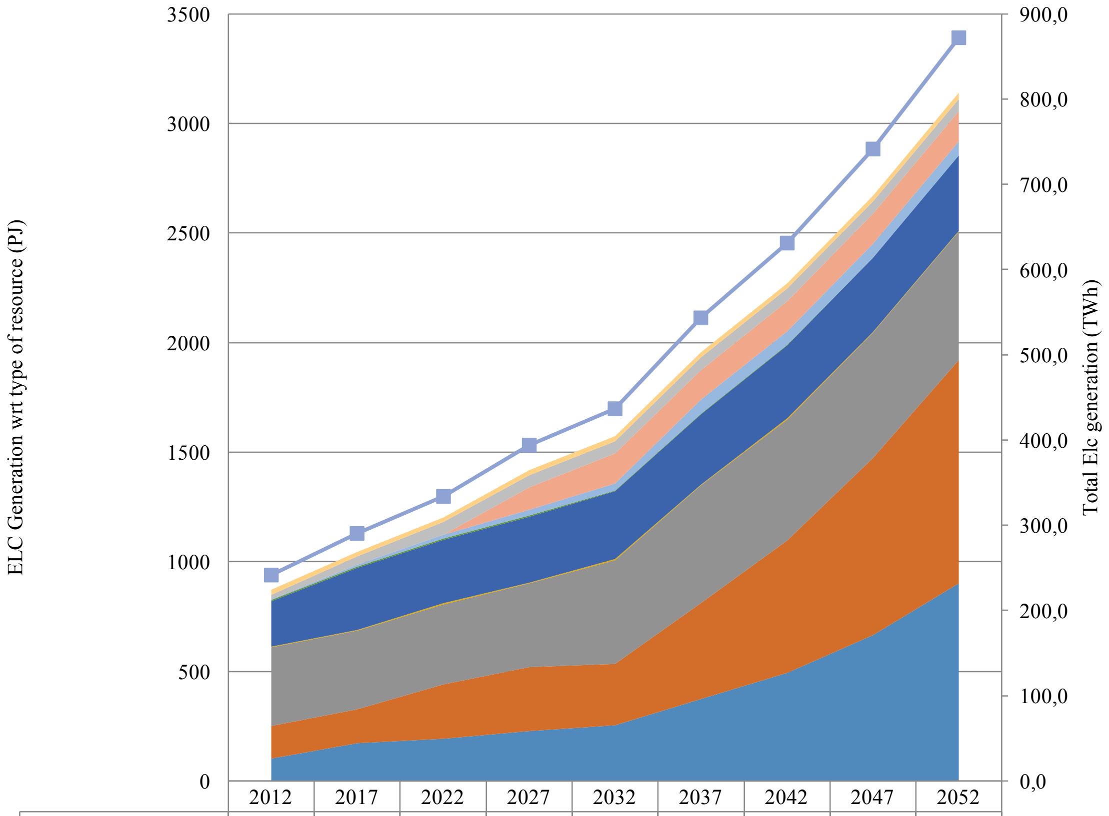
6.2.5. Power Sector

This section examines how a carbon price is likely to affect emissions from the electricity sector, which accounts for about one third of Turkey’s greenhouse gases. By raising the variable costs of producing electricity from fossil fuels by introducing carbon tax, an incentive will be established to shift towards cleaner technologies. Respective system response on fuel consumptions under carbon tax options are given in Table 6.7.

Regarding power sector, when \$10 tax per ton of CO_2 is levied on the system, it has a potential to reduce 38.86 Mton CO_2 within the time span of the model (2012-2052). This value corresponds to 1% of the total amount of emissions released. Therefore, total emissions do not significantly differ from BAU. Numbers reveal that the threshold value is \$20 to provide a substantial amount of emission mitigation with 176.12 Mton of CO_2.

In CO2_20_BM scenario, consumptions of hard coal and lignite have decreased by 11,62% and 3,23% respectively. In tax level of \$20, electricity generation from geothermal power and solar remain constant, whereas wind energy reaches 56,7 PJ and it attains its highest electricity generation with a tax of \$30 per ton of CO_2. Consequently, wind energy is promoted by the model with the tax level of \$20. Electricity generation from solar energy starts increasing at a meaningful level after an emission tax equal or greater than \$30 emission tax is levied.

To compare model results, electricity production values with respect to fuel types under \$50 emission tax in TIMES_TR model are given in Figure C.8. Wind nuclear power and hydro power reaches the same maximum level in both models. Electricity production from lignite sources reach 1018PJ value in 2052 year according to BUEMS_TR, and 943PJ according to TIMES_TR. BUEMS_TR model predicts total electricity production will reach 872TWh, while TIMES_TR predicts this value to be 830 TWh.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Electricity-IMP	21	21	21,4	22,1	22,5	23,7	24,9	26,1	27,5
Wind	21,5	38,3	56,9	56,9	56,9	56,9	56,9	56,9	56,9
Nuclear	0	0	0	102,2	136,2	136,2	136,2	136,2	136,2
Solar	3	9,1	18,9	26,5	31,5	63,1	63,1	63,1	63,1
RFO	4,8	5	4,5	4,1	3,3	2,5	1,7	0,8	0
Hydro	208	282,7	290,3	302,2	310,3	321,7	334,5	338,9	345
Geothermal	3,3	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Natural Gas	359,7	358,8	365,4	381,6	473,7	536,7	553,5	570,3	587,1
Lignite	146,3	154,7	248,2	290,8	280,9	438,6	603,5	808	1018,2
Hard Coal	103,5	172	192,6	227,9	253,6	372,3	492,8	666,3	901,1
Total	242,0	290,4	333,9	393,9	436,8	543,2	630,8	741,8	871,9

Figure 6.18. Electricity generation wrt the fuel type under CO2_50_BM (PJ).

In BAU scenario, Turkish electricity sector heavily rely on coal (39%, including hard coal and lignite), hydroelectric power usage (with 11% of total consumption), and natural gas (44%) by year 2012. Also, electricity generation increases by 4.5 times during 2012-2052 to meet continuously increasing electricity demand in the end-use sectors. Over 80% of total electricity generation comes from fossil fuels (hard coal, lignite and natural gas) in the reference scenario in 2012. In the absence of policy instruments that strictly charges the greenhouse gas emissions, coal turns out to be the dominant source of energy in power sector.

Table 6.7. Electricity generation wrt the type of fuel (PJ).

CO2_10_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	103,5	174,2	194,0	228,0	253,7	372,4	492,8	666,3	901,1
Lignite	146,3	171,8	286,2	458,0	467,8	650,1	877,1	1160,2	1467,8
Natural gas	359,7	358,8	365,4	381,6	485,6	536,7	553,5	570,3	587,1
Geothermal	3,3	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Hydro	208,0	282,7	290,3	302,2	310,3	321,7	334,5	338,9	345,0
RFO	7,7	5,0	4,5	4,1	3,3	2,5	1,7	0,8	0,0
Solar	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Uranium	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Wind	21,5	17,6	17,6	17,7	17,7	17,8	17,9	18,0	18,1
Electricity	21,0	21,0	21,4	22,1	22,5	23,7	24,9	26,1	27,5
CO2_20_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	103,5	172,6	192,6	227,9	253,6	372,3	492,8	666,3	901,1
Lignite	146,3	157,9	259,4	418,9	428,7	611,1	836,8	1029,6	1334,0
Natural gas	359,7	358,8	365,4	381,6	485,6	536,7	553,5	570,3	587,1
Geothermal	3,3	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Hydro	208,0	282,7	290,3	302,2	310,3	321,7	334,5	338,9	345,0
RFO	7,7	5,0	4,5	4,1	3,3	2,5	1,7	0,8	0,0
Solar	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Uranium	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Wind	21,5	34,5	43,9	47,5	50,1	52,7	55,8	56,1	56,9
Electricity	21,0	21,0	21,4	22,1	22,5	23,7	24,9	26,1	27,5
CO2_30_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	103,5	172,6	192,6	227,9	253,6	372,3	492,8	666,3	901,1
Lignite	146,3	149,9	244,6	422,1	425,0	560,2	791,8	1038,1	1245,9
Natural gas	359,7	358,8	365,4	381,6	485,6	536,7	553,5	570,3	587,1
Geothermal	3,3	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Hydro	208,0	282,7	290,3	302,2	310,3	321,7	334,5	338,9	345,0
RFO	7,7	5,0	4,5	4,1	3,3	2,5	1,7	0,8	0,0
Solar	0,0	3,8	3,8	3,8	3,8	3,8	3,8	3,8	3,8
Uranium	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Wind	21,5	38,5	56,9	56,9	56,9	56,9	56,9	56,9	56,9
Electricity	21,0	21,0	21,4	22,1	22,5	23,7	24,9	26,1	27,5
CO2_50_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	103,5	172,0	192,6	227,9	253,6	372,3	492,8	666,3	901,1
Lignite	146,3	154,7	248,2	290,8	280,9	438,6	603,5	808,0	1018,2
Natural gas	359,7	358,8	365,4	381,6	473,7	536,7	553,5	570,3	587,1
Geothermal	3,3	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7
Hydro	208,0	282,7	290,3	302,2	310,3	321,7	334,5	338,9	345,0
RFO	4,8	5,0	4,5	4,1	3,3	2,5	1,7	0,8	0,0
Solar	3,0	9,1	18,9	26,5	31,5	63,1	63,1	63,1	63,1
Uranium	0,0	0,0	0,0	102,2	136,2	136,2	136,2	136,2	136,2
Wind	21,5	38,3	56,9	56,9	56,9	56,9	56,9	56,9	56,9
Electricity	21,0	21,0	21,4	22,1	22,5	23,7	24,9	26,1	27,5

Coal is the basic source of the CO_2 emissions that belong to the power sector in 2052, in the decarbonisation pathway, nuclear and renewable generation such as wind, biomass, marine and solar should be involved into the base-line electricity generation process under higher emission tax rates. Numbers reveal that carbon tax is quite effective in electricity sector, it causes very large reductions in the use of coal. In 2032, in BAU scenario the amount of hard coal and lignite used to produce electricity are 347,4 PJ and 409,3 PJ respectively. Whereas under the market where government excises $50 tax per ton of CO_2 these values decrease to 253,6 PJ and 280,9 PJ. As a result, the percentages of coal and lignite in power sector diminish and to about 16,8% and 28%.

6.2.6. Fuel Supply

This section describes the effect of emission tax scenarios on fuel consumption of the Turkish Energy Sector. Highest system response is obtained under $50 emission case is given in Table 6.8.

Table 6.8. Energy consumption values under CO2_50_BM scenario.

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Asphaltite	6	26	29	33	35	42	50	57	65
Hard Coal	994	1.199	1.342	1.571	1.728	2.300	2.846	3.508	4.364
Lignite	659	677	948	1.444	1.475	1.890	2.513	3.220	3.535
Electricity	746	866	982	1.182	1.298	1.600	1.918	2.284	2.671
Natural Gas	1542	1.969	2.225	2.540	2.892	3.303	3.611	4.095	5.061
Diesel	655	861	939	1.047	1.126	1.279	1.344	1.551	1.802
Distillate Oil	9	5	7	10	11	8	12	13	11
Gasoline	79	157	211	293	352	530	812	958	1.094
Jet Fuel	162	225	236	266	278	325	376	426	444
Kerosene	2	2	2	3	3	4	5	6	7
LPG	175	140	136	130	125	140	147	170	197
RFO	45	44	43	48	51	50	52	55	58
Petroleum coke	112	154	181	228	260	350	447	567	711
Biomass	146	169	180	196	208	241	280	324	376
Ethanol	0	0	0	0	0	11	16	24	29
Geothermal	97	96	98	101	103	109	114	120	97
Hydrogen	0	0	0	0	1	3	5	7	9
Hydro	202	283	290	302	310	322	334	339	345
Solar	32	79	82	87	89	96	105	113	99
Wind	18	39	57	57	57	104	104	104	104
Cruide Oil	1035	2.547	2.780	3.109	3.344	3.787	3.988	4.599	5.332

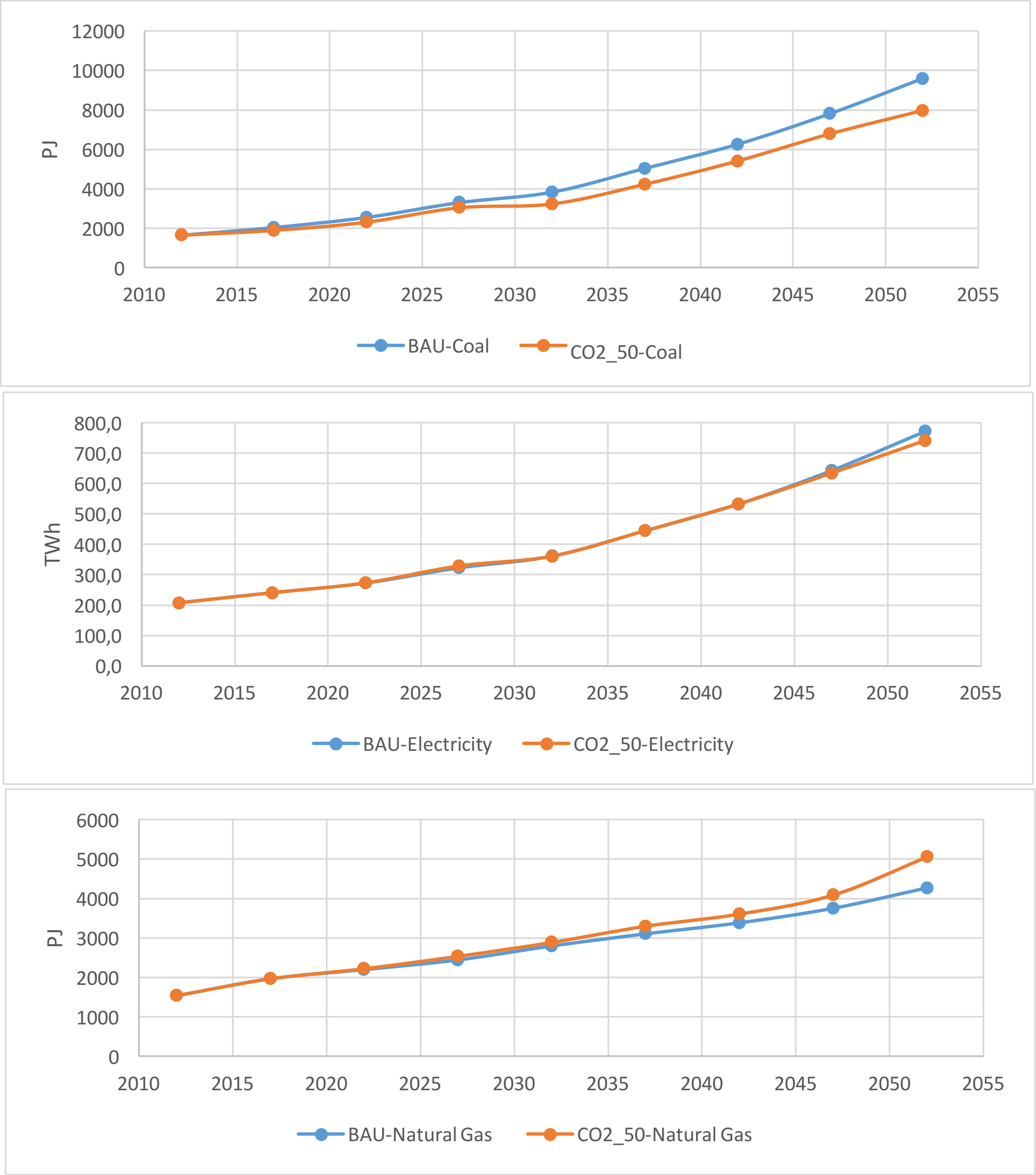


Figure 6.19. Fuel consumptions under BAU_BM and CO2_50_BM.

Table 6.8 includes anticipated fuel consumptions that belong to end use demand sector sectors and power sector. It is projected that the consumption of hard coal is anticipated to decrease by 15.5%. However, the lignite consumption is not expected to scale down to the same extent as hard coal, and its reduction level remains 10.5%. The impact of carbon tax on the system is limited in comparison with the bound scenarios.

The vast majority of the increase in the natural gas consumption (accounted for 9.54% compared to BAU level) is due to Power Sector and Industry Sector. Regarding Transport Sector, the energy consumptions decrease for LPG and diesel is equal to 5.78PJ and 85.73PJ respectively. The system gets vehicle technologies that consume electricity and hydrogen into use when $50 emission tax is imposed.

The overall impact of the emission tax that is less than $30 can be summarized as the shift toward more efficient technologies rather than a change of fuel consumption structure sharply. 5531PJ decrease in the coal consumption is anticipated whereas only 35.4PJ increase in the electricity consumption is expected. It is not wrong to argue that, emission tax scenarios are not quite effective in comparison with emission bound scenarios.

6.2.7. Emissions

The burden of carbon tax is distributed over all demand areas (residential, commercial, industrial, agriculture and transport) and supply side including power sector. The average mitigation costs are same in scenarios regardless of sectors and fuel types. The system response under the emission tax scenarios in terms of total greenhouse gas emissions is presented in Table 6.9. In this section, the CO_2 emissions that belong to the carbon tax scenarios are presented first and followed by a discussion of sources of emissions reductions resulted from CO_2 tax. Within the policy family of tax applications to discourage CO_2 emissions, mitigation values indicate that $10 emission tax does not have a significant effect on the system as a whole. None of the sectors shows a significant decrease in their emission levels.

Scenario results reveal that the sector with the highest contribution to emission mitigation in the case of a carbon tax is the power sector as can be illustrated in Figure 6.20. In $20, $30 and $50 cases 48%, 55% and 57% of the total reduction is provided by the power sector respectively.

Industry sector is one of the prominent sectors that contribute the most to the emission reduction in these scenarios. By the time all other sectors start to react with the help of increasing taxes, a gradual decrease in the contribution of the industry sector to the emission reduction is observed.

Table 6.9. BUEMS model emission values under CO_2 tax scenarios (Mton CO_2).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Agriculture	3,3	4,4	5	5,7	6,2	7,3	8,6	9,9	11,1
Res. and Com.	63,9	78,4	92,4	106,1	116,8	146,5	181,8	212,2	244,2
Transport	66,1	89,6	97,6	110,4	118,3	140,3	160,2	184,3	205,4
Refinery	12,8	20,8	23	25,1	25,4	32,9	36,9	42,6	45,5
Power	126,1	153,9	195	247,3	271,3	360,8	457	579	720,1
Industry	75,4	104,7	119,1	147,9	165,6	199,6	226,6	260	300,6
CO2_10_BM	347,6	451,8	532,1	642,5	703,6	887,4	1071,1	1288	1526,9
Agriculture	3,3	4,32	4,6	5,2	5,9	6,9	8,3	9,2	10,1
Res. and Com.	63,9	78,1	89,3	106,1	116,8	146,5	174,2	216,4	244,1
Transport	66,1	89,6	97,6	110,4	119,6	140,5	159,2	184,4	206,6
Refinery	12,8	20,8	23	26,1	28,3	32,9	34,9	42,6	47,5
Power	126,1	149,3	186,7	243,8	261	348,9	443,7	540,1	680,7
Industry	75,4	104,4	118,3	142,8	160,2	193,7	218,5	254,2	295
CO2_20_BM	347,6	446,52	519,5	634,4	691,8	869,4	1038,8	1246,9	1484
Agriculture	3,3	4,32	4,6	5,2	5,9	6,9	8,3	9,2	10,1
Res. and Com.	63,9	75	88	103,7	113,8	142,4	171,2	210,7	243,1
Transport	66,1	89,5	97,3	109,7	117,8	137,3	154,8	176,3	193
Refinery	12,8	19,1	23	26,1	28,3	32,9	32,9	42,6	47,5
Power	126,1	146,2	182,3	244,8	259,9	333,9	431,4	542,7	682,9
Industry	75,4	102,8	116,7	140,9	158,1	191,5	218	251,3	292,6
CO2_30_BM	347,6	436,92	511,9	630,4	683,8	844,9	1016,6	1232,8	1469,2
Agriculture	3,3	4,32	4,6	5,2	5,9	6,9	8,3	9,2	10,1
Res. andCom.	63,9	65,5	76,4	88,8	95,6	142,5	175	213,1	244,5
Transport	66,1	89,4	97,2	108,4	116,4	132,1	148,8	168,1	184,5
Refinery	12,8	20,7	22,9	25,9	28,1	32,8	31,9	42,2	47,2
Power	125,2	142,2	170,5	187	198,4	258,9	351,6	470,9	576,2
Industry	75,4	102,3	115,6	138,6	155,6	188,4	214,5	249,1	287,6
CO2_50_BM	346,7	424,42	487,2	553,9	600	761,6	930,1	1152,6	1350,1

Transportation sector makes its contribution to the emission reduction by switching to highly efficient technologies. Percentage of the contributions of each sector to emission reduction in BAU scenario is illustrated in the Table 6.10.

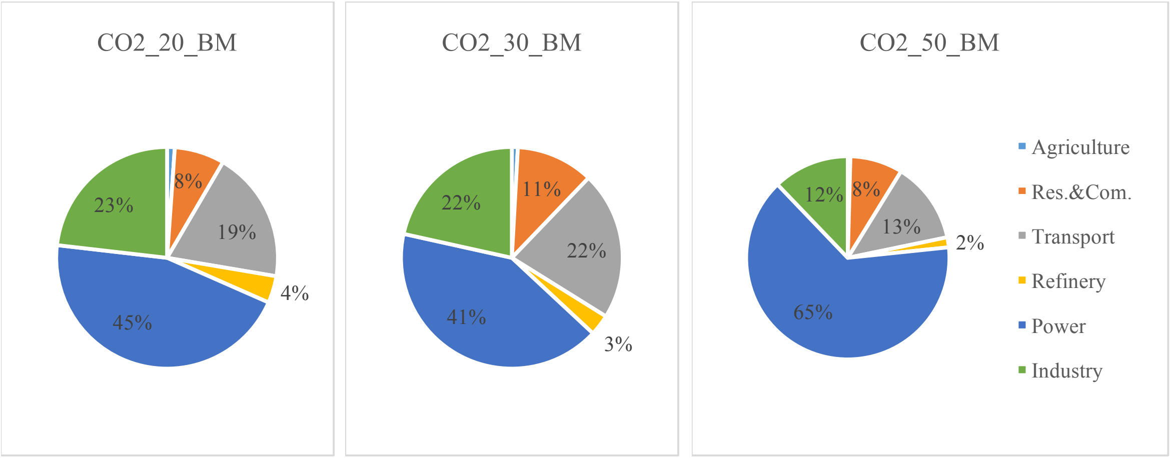


Figure 6.20. Contribution of sectors on emission mitigation (%).

From the year 2015 and onwards, \$10 tax per ton of CO_2 provides only 2% decrease in emissions in the system whereas under \$20 case total emissions are anticipated to be reduced by 5% and \$30 tax results in 6% reduction of the total emissions. In the case of Turkish Energy Sector, the most meaningful emission reduction is observed with a \$50 tax on each ton of emission. As \$50 emission tax is introduced to the system, BAU scenario states that 14% of total emissions will be avoided with 1047 Mton CO_2 reduction potential of the tax.

Table 6.10. Emission reduction values wrt BAU under CO_2 tax scenarios (%).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
CO2_10_BM	0,00	0,02	0,01	0,01	0,02	0,01	0,02	0,04	0,05
CO2_20_BM	0,00	0,03	0,04	0,03	0,04	0,03	0,05	0,07	0,08
CO2_30_BM	0,00	0,04	0,05	0,03	0,05	0,06	0,07	0,08	0,09
CO2_50_BM	0,00	0,08	0,10	0,15	0,17	0,15	0,15	0,14	0,16

6.2.8. System Cost

Changes in the system cost under emission tax are listed in Table 6.11. As a number of tax increases (\$10-\$20-\$30) the priority is given to more efficient technologies. After the tax reaches the \$50 level, investments are shifted towards technologies utilizing alternative fuels.

Imposing \$30 emission tax for emission mitigation creates an additional cost of 9686 Million US\$ in total system cost (throughout the planning horizon) whereas in \$50 tax scenario this number reaches 42876 Million US\$.

Table 6.11. BUEMS model total system cost (2012 Million US \$).

	2012	2017	2022	2027	2032	2037	2042	2047	2052
BAU_BM	1217698	1887911	2157722	2557338	2833471	3915330	4918299	5459447	6056581
CO2_10_BM	1217698	1887954	2157770	2557388	2833569	3915387	4918433	5459781	6057076
CO2_20_BM	1217698	1888174	2158168	2557618	2833972	3915800	4919121	5460513	6057623
CO2_30_BM	1217698	1888815	2158570	2557939	2834560	3916764	4920255	5460725	6058233
CO2_50_BM	1217698	1890033	2160972	2562812	2838899	3921910	4926083	5465393	6062848

Average of differences in total system costs are 12% between TIMES_TR and BUEMS_TR. Cost values for emission tax scenario of TIMES_TR model are given in Table C.1. TIMES_TR model forecasts a 157.434 million \$ cost increase with investments made under \$30 emission tax. This value is 179.869 million \$ for \$50 emission tax. The marginal costs that provided by BUEMS_TR for emission mitigation that gathered from system under emission bound scenarios are illustrated in Table 6.12.

Table 6.12. Cost of mitigation (\$/ton of CO_2).

	2012	2017	2022	2027	2032	2037	2042	2047	2052	Avg
CO2_10_BM	0	13,4	16,4	11,2	8,6	8,6	7,9	7,1	6,1	9,9
CO2_20_BM	0	31,0	28,8	22,2	21,6	19,1	16,7	12,1	8,4	20,0
CO2_30_BM	0	50,0	36,7	36,2	34,9	29,2	27,4	12,5	11,9	29,9
CO2_50_BM	0	69,4	68,0	58,8	47,2	49,7	49,3	32,6	24,3	49,9

Average emission reduction cost is obtained as \$9.9 per ton in CO2_10_BM scenario whereas this cost is calculated for CO2_20_BM, CO2_30_BM and CO2_50_BM as \$20, \$29,9 and \$49,9 respectively.

6.3. Emission Bound Scenario Results

6.3.1. Power Sector

Under emission bound scenarios, power sector shows the highest response. The electricity generation with respect to the fuel types are presented in Table 6.13.

Table 6.13. Electricity generation by source (TWh).

BAU_10_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	28,8	48,5	54,0	63,4	70,5	103,5	139,9	187,5	250,3
Lignite	40,6	44,9	60,9	91,9	97,1	138,4	196,3	273,7	353,3
Natural Gas	99,9	99,7	105,5	111,2	134,0	148,3	152,9	157,6	162,3
Geothermal	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Hydro	57,8	78,5	80,6	83,9	86,2	89,4	92,9	94,1	95,8
RFO	1,3	1,4	1,3	1,1	0,9	0,7	0,5	0,2	0,0
Solar	0,7	8,7	9,9	11,7	12,9	15,9	15,9	15,7	13,6
Nuclear	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Wind	6,0	6,2	6,3	7,1	7,2	7,7	7,8	7,9	8,1
Imported ELC	5,8	5,8	5,9	6,1	6,3	6,6	6,9	7,3	7,6
Total	242,0	284,8	325,4	377,5	416,2	511,3	614,1	745,0	892,0
BAU_20_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	28,8	50,8	56,3	66,8	73,9	111,8	147,6	194,2	255,0
Lignite	40,6	42,3	48,3	78,9	87,9	126,3	173,9	194,9	247,0
Natural Gas	99,9	99,9	100,0	103,5	122,0	132,2	134,3	136,4	138,6
Geothermal	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Hydro	57,8	78,5	80,6	83,9	86,2	89,4	92,9	94,1	95,8
RFO	1,3	1,4	1,3	1,1	0,9	0,7	0,5	0,2	0,0
Solar	0,7	8,7	9,9	11,7	12,9	15,9	18,9	21,8	24,8
Nuclear	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Wind	6,0	7,1	7,5	7,9	8,7	9,3	9,7	9,8	10,3
Imported ELC	5,8	5,8	5,9	6,1	6,3	6,6	6,9	7,3	7,6
Total	242,0	270,3	310,9	361,1	399,8	493,2	585,6	659,8	780,2
BAU_25_BM	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Hard Coal	28,8	50,8	56,3	66,8	73,9	106,9	147,6	170,3	173,2
Lignite	40,6	42,8	45,9	76,1	77,8	91,8	129,8	183,6	234,5
Natural Gas	99,9	99,9	99,6	103,5	123,5	132,2	134,3	139,0	143,7
Geothermal	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Hydro	57,8	78,5	80,6	83,9	83,8	89,4	92,9	94,1	95,8
RFO	1,3	1,4	1,3	1,1	0,9	0,7	0,5	0,2	0,0
Solar	0,7	8,7	9,9	11,7	11,7	15,9	18,9	21,8	24,8
Nuclear	0,0	0,0	0,0	0,0	28,4	37,8	37,8	37,8	37,8
Wind	6,0	10,3	13,2	15,7	15,7	16	16	16	16
Imported ELC	5,8	5,8	5,9	6,1	6,3	6,6	6,9	7,3	7,6
Total	241,9	272,8	313,7	365,9	403	498,3	585,7	671,0	734,4

It is observed that the share of renewable resource consumption by power sector increases directly proportional to the introduction of higher emission constraints.

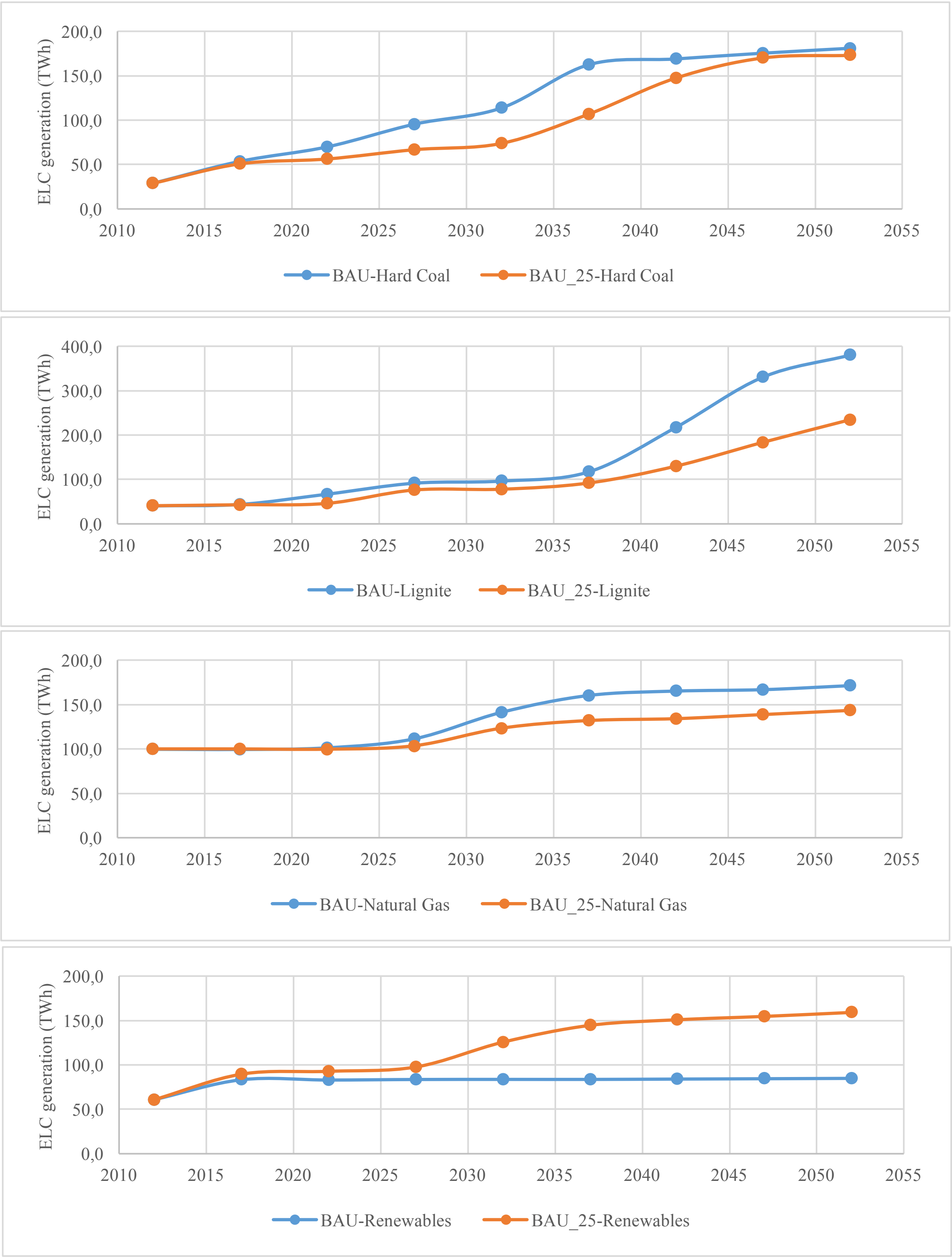


Figure 6.21. Electricity generation emission bound scenarios (TWh).

Fuel consumptions in the BAU scenario are described in the section 6.1.6 in a detailed way for this reason only the discussion about bound scenarios is given.

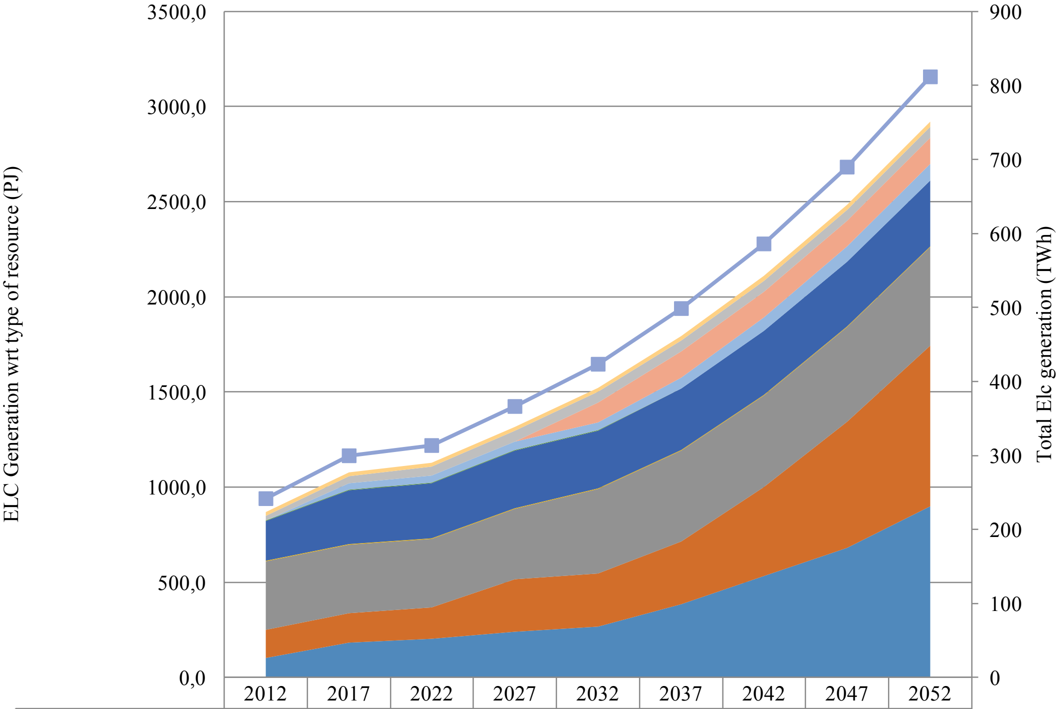
It is clear that emission bounds are successful policy instruments to discourage CO_2 emissions. As illustrated from Figure 6.21, 25% bound on total emissions will encourage the consumption of renewables with an increasing trend.

In BAU scenario, electricity production from renewable resources starts with the value of 60.8TWh, and this value reaches 83,9 TWh in 2032 and finally 85,1 TWh in 2052. For the years 2032 and 2052, BAU_25_TM scenario predicts 125,8TWh and 159,4 TWh respectively. It is observed that the system invests in nuclear energy only if a 25% emission restriction is included in the system.

Solar power is not preferred in BAU scenario. However, under emission restrictions, solar power provides a total of 105TWh electricity generation in BAU_10_BM scenario for 2012-2052 period. Furthermore, this value reaches 125,3 TWh with the BAU_20_BM scenario. It can be argued that as the level of emission bound increases, solar power is going to be favored.

Wind energy is not preferred in BAU scenario due to low-efficiency availability. It is clear that the lower price of coal in comparison with other energy resources prevents the use of renewable resources. However, this situation changes under policy family that restricts total emission values. The model promotes renewable resources and other fuel types with low emission values per unit to meet the total reduction goal. The same condition applies for the wind power. In BAU_20_BM scenario 8.7TWh of electricity is produced in 2032 and this value jumps to 10.3 TWh at the end of the analysis. BAU_25_BM values show 16TWh of electricity production in 2052.

When natural gas is focused on, it can be seen that the share of natural gas in electricity production is not volatile, and it always is one of the most important source of fuel for electricity generation. In BAU_10_BM scenario, 28.44% of the total electricity production is provided by using natural gasses and this rate increases to 29.29% with the BAU_25_BM scenario.



	2012	2017	2022	2027	2032	2037	2042	2047	2052
Electricity-IMP	21,0	20,9	21,2	22,0	22,7	23,8	24,8	26,3	27,4
Wind	21,5	37,1	47,5	56,5	56,5	57,6	57,6	57,6	57,6
Nuclear	0,0	0,0	0,0	0,0	102,2	136,1	136,1	136,1	136,1
Solar	0,0	31,3	35,6	42,1	42,1	57,2	68,0	78,5	89,3
RFO	4,8	5,0	4,7	4,0	3,2	2,5	1,8	0,7	0,0
Hydro	208,0	282,6	290,2	302,0	301,7	321,8	334,4	338,8	344,9
Geothermal	3,7	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6
Natural Gas	359,7	359,6	358,6	372,6	444,6	475,9	483,5	500,4	517,3
Lignite	146,3	154,1	165,2	274,0	280,1	330,5	467,3	661,0	844,2
Hard Coal	103,5	182,9	202,7	240,5	266,0	384,8	531,4	680,8	900,4
Total	241,2312	299,2	313,7	365,9	423	498,3	585,7	689,9	811,3

Figure 6.22. Electricity generation wrt the fuel type under BAU_25_BM (PJ).

Numbers indicate a declining trend in lignite consumption. BAU_10_BM scenario predicts 97,1 TWh of electricity generated by power plants consuming lignite in 2032 and this value reaches 353,3 TWh in 2052. But for the same year electricity generation shifts from lignite to other sources due to tight emission bound constraint under BAU_20_BM and BAU_20_BM cases. As a result, 297TWh and 234,5 TWh of electricity production belong to lignite respectively.

Electricity production values are given in Figure C.12 in TIMES_TR model. In 2032, total electricity production is 406 while this value is 423TWh in BUEMS_TR. TIMES_TR predicts a production of 806 TWh in 2052. This value is 811TWh in BUEMS_TR.

Electricity production from natural gas resources are higher than that of BUESM_TR scenario (530TWh in 2052). Electricity production from lignite sources are 5% lower than BUEMS_TR values in TIMES_TR.

6.3.2. Fuel Supply

In this section, change in the structure of Turkish Energy Sector fuel consumptions under emission bound scenario comparing to BAU will be explained.

Table 6.14. Energy consumption values provided under BAU_25_BM.

	2012	2017	2022	2027	2032	2037	2042	2047	2052
Asphaltite	6	6	6	6	6	6	6	5	0
Hard Coal	994	974	1101	1295	1535	2044	2515	3105	3852
Lignite	659	214	525	796	790	1052	1398	1968	2480
Electricity	746	777	884	1030	1148	1429	1670	1988	2361
Natural Gas	1542	2134	2352	2717	3023	3667	4096	4629	5350
Nuclear	0	0	0	0	310	413	413	413	413
Diesel	655	353	475	610	729	925	1384	1595	1784
Distillate Oil	9	28	38	85	68	21	90	123	206
Gasoline	79	272	269	289	347	525	810	964	1092
Jet Fuel	162	196	222	161	191	273	281	252	168
Kerosene	2	3	2	3	3	4	5	6	7
LPG	175	146	155	168	158	154	101	121	143
RFO	45	42	42	52	52	54	53	57	60
Petroleum coke	112	133	171	206	217	350	447	567	711
Biomass	146	151	177	196	208	241	280	324	376
Ethanol	2	8	8	9	10	16	25	28	33
Geothermal	97	96	98	101	103	109	114	120	97
Hydrogen	0	0	0	6	6	6	6	54	63
Hydro	202	283	290	302	301	322	334	339	345
Solar	32	164	193	238	255	345	424	510	632
Wind	18	14	12	10	9	12	12	12	12
Crude Oil	1035	1035	1420	1637	1762	1762	3702	4397	4951

In order to reveal the highest deviation comparing to BAU scenario, fuel consumptions under BAU_25_BM will be focused on. Although, the share of coal consumption shows no sudden decrease under low carbon tax and low emission bound, because the system prefers paying tax rather than investing in nuclear energy. This behavior of BUEMS is observed to change, as higher levels of tax and 25% emission bound are applied.

The most intriguing finding is that, BUEMS activates nuclear power plant in 2032 only under constraint of 25% reduction is introduced into the model. Neither fuel switching nor efficiency increase is able to prevent investment in nuclear energy (The transformation of electricity generation under emission bound scenarios is explained in the part 6.3.1).

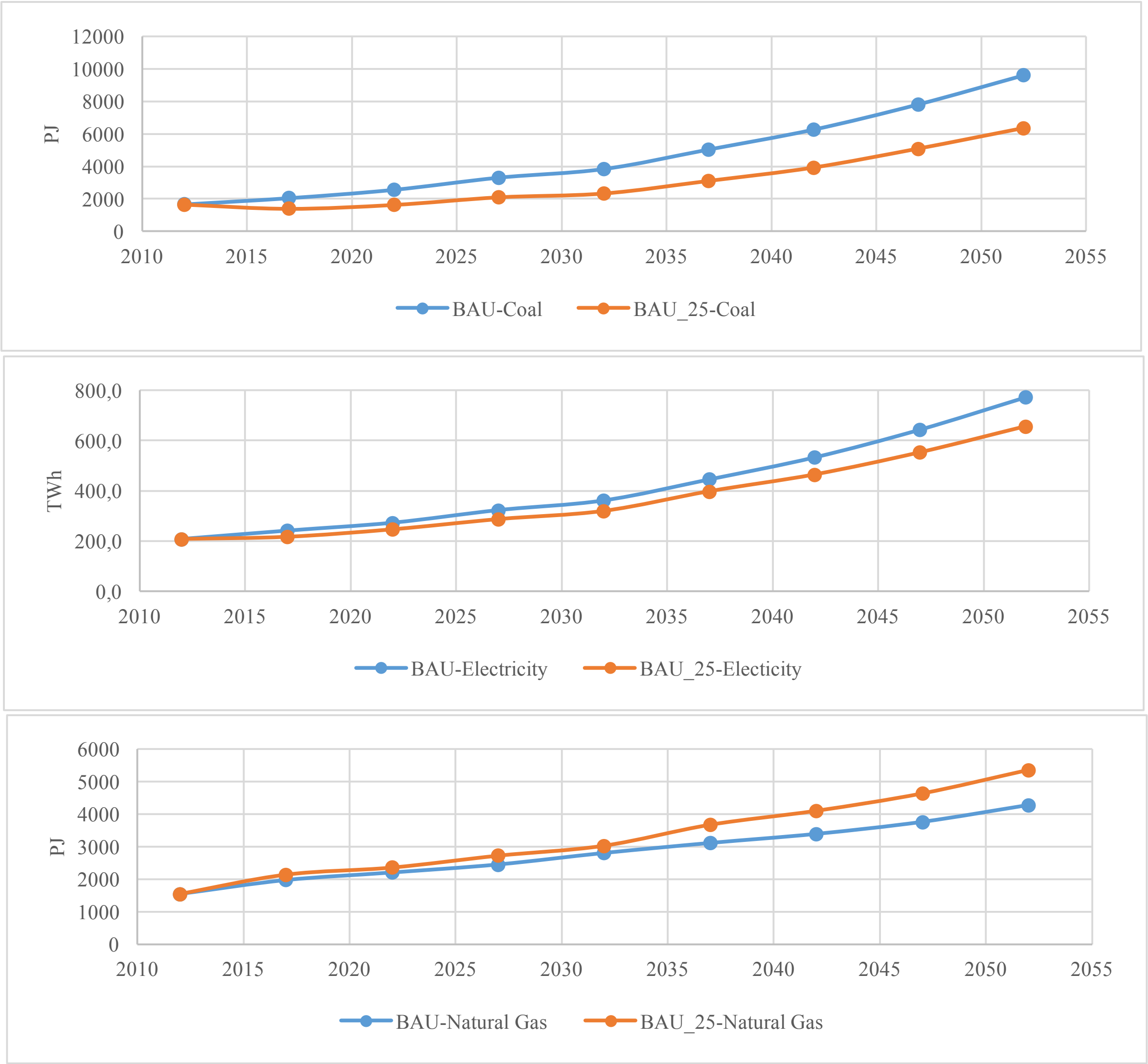


Figure 6.23. Fuel consumptions under BAU_BM and BAU_25_BM.

In the 2012-2052 period, it is important to note that, transport sector decreases its emissions by cutting its diesel usage first by 19%. Nevertheless, gasoline production only increases 3% which is a sign of the positive change in the vehicle technology efficiency. The reaction of the transport sector is logical when emission factors are taken into consideration, the emission coefficient of diesel is higher than that of gasoline. Usage of vehicles running with electricity (Car Battery Vehicle) and hydrogen-burning vehicles explains the decrease in the use of diesel. Total hydrogen consumption is calculated as 140PJ. An increase in efficiency in air transport is also observed. A total of 921PJ is saved with these advances.

The change in the consumption patterns that belong to three main groups is given in Figure 6.23 (Note that coal section consists of three different components namely asphaltite, hard coal and lignite). Coal consumption in BAU starts with 1659Pj in 2012 and is expected to hit 3307 by 2032. On the other hand in BAU_25_BM scenario consumption value that belong to 2032 is anticipated to reach 2032. It can be argued that under 25% emission bound case, the 19% increase in natural gas and 455 PJ increase in electricity compensates for the 35% decrease in total coal consumption as illustrated in Figure 6.23.

Natural gas is the most convenient fuel to replace coal consumption (this applies for only some production processes) and it has a consumption increase of 15.8%. If we look only 2032 and onwards within the modeling period, that percentage is equal to 17,4% of that consumption level. Therefore, the dependence of the country on foreign sources gradually increases. The change levels of other fuels are listed in Table 6.14.

6.3.3. Emissions

Changes related to the emissions are given for 3 different emission bound scenarios on a sectoral basis. In total, 10%, 20% and 25% emission reduction bound (they are calculated in accordance with BAU emission levels (process emissions are left out of these constraints)) are introduced into the model for period starting from 2017 to 2052.

Table 6.15. BUEMS model total emissions under bound scenarios (Mton CO_2).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Agriculture	3,3	4,5	5,1	5,9	6,5	8,0	9,4	10,8	12,1
Res. and Com.	63,9	78,4	92,4	106,9	116,8	146,5	181,8	223,8	259,6
Transport	66,7	91,7	100,6	114,6	124,8	148,6	173,8	201,6	227,5
Refinery	12,8	23,8	26,0	29,0	31,1	35,2	37,2	43,0	48,1
Power	125,2	154,2	194,7	247,3	272,4	356,6	462,0	595,4	749,2
Industry	76,2	106,5	121,1	148,7	169,5	206,0	233,1	270,6	322,8
BAU_BM	345,1	454,9	535,2	647,5	715,1	893,5	1088,5	1335,3	1607,9
Agriculture	3,3	4,5	5,1	5,9	6,5	8,0	9,4	10,8	12,1
Res. and Com..	63,9	70,0	82,2	100,6	114,4	141,9	175,8	211,4	254,3

Table 6.15. BUEMS model total emissions under bound scenarios (Mton CO2) (cont.)

	2012	2017	2022	2027	2032	2037	2042	2047	2052
Transport	66,7	87,9	93,8	104,3	111,8	131,3	152,6	176,2	197,6
Refinery	12,8	10,8	16,4	24,7	26,6	31,6	36,9	42,8	47,9
Power	125,2	139,1	175,1	217,8	237,5	315,4	406,2	526,9	662,2
Industry	76,2	100,9	113,5	134,0	152,2	182,8	206,7	242,6	283,3
BAU_10_BM	348,1	413,2	486,1	587,4	649,0	811,0	987,6	1210,8	1457,4
Agriculture	3,3	4,4	5,0	5,7	6,2	7,3	8,6	9,9	11,1
Res. and Com.	63,9	62,0	73,0	90,2	103,6	137,0	169,2	209,3	251,9
Transport	66,7	85,7	93,8	103,6	109,4	124,2	143,5	161,2	176,5
Refinery	12,8	9,8	11,3	13,4	18,8	19,4	24,8	29,8	34,5
Power	125,2	116,0	147,2	182,0	196,3	260,6	336,2	435,1	547,4
Industry	76,2	89,4	101,7	127,2	142,6	172,3	195,5	230,9	274,0
BAU_20_BM	348,1	367,3	432,1	522,1	576,9	720,9	877,9	1076,2	1295,4
Agriculture	3,3	4,2	4,8	5,6	6,1	7,3	8,7	9,9	11,1
Res. and Com.	63,9	61,7	70,8	88,0	103,1	134,1	164,5	197,0	233,3
Transport	66,7	72,2	84,4	90,8	98,7	121,4	143,8	159,3	174,8
Refinery	12,8	0,2	5,3	5,7	19,5	19,5	24,8	30,0	35,0
Power	125,2	115,4	137,9	175,1	169,2	222,4	288,0	383,9	488,5
Industry	76,2	90,6	101,9	124,3	144,2	171,1	193,4	228,9	271,8
BAU_25_BM	348,1	344,4	405,1	489,5	540,8	675,8	823,0	1009,0	1214,5

The reactions of all sectors under 10%, 20% and 25% emission bound scenario are given in Table 6.15. Each sector's contribution on emission mitigation is illustrated in Figure 6.24.

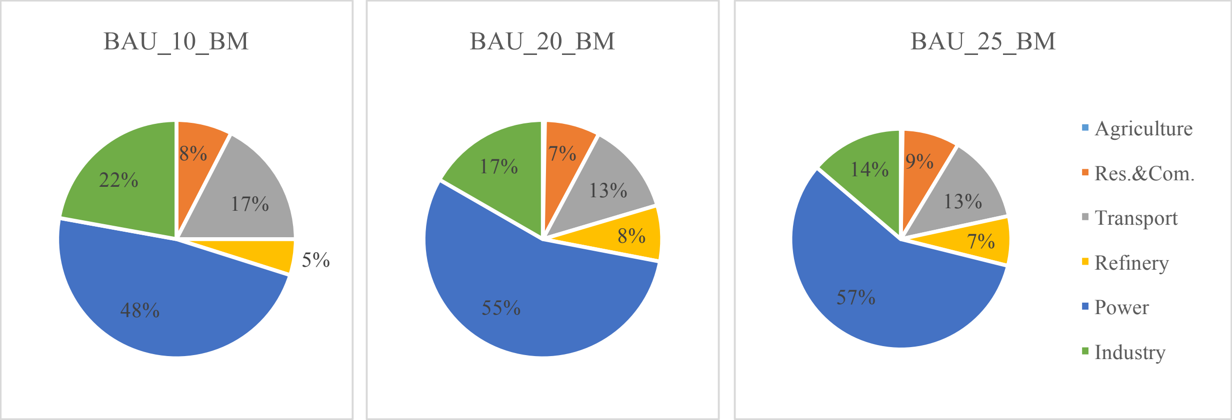


Figure 6.24. Contribution of sectors on emission mitigation (%).

Highest response to the emission bound scenarios among all sectors is given by power sector. The shift in the electricity generation is explained in detail in Section 6.3.1.

When the 10% emission constraint is added to the system, the lowest contribution to total emission mitigation is provided by refinery sector with 5%. Residential and commercial sector follows refinery sector with 8% contribution. The most crucial change in residential and commercial sector is the decrease of the coal consumption for heating. This decrease amounts to 1069,3PJ for the period 2012-2052.

Industry sector abates its total emission by 162 Mton CO_2. If the underlying reason for the reduction of CO_2 emissions is further investigated, it is seen that the mitigation is due to the increase in the total amount of natural gas consumption with additional 1795PJ. Chemicals and Fertilizer Industry and Glass and Non-Metal Minerals Industry also give a raise to the share of natural gas in meeting their demand for process heat and machine drive. From 2025 onwards, Cement Industry gains in its emission output due to the average of 16% efficiency boost in lignite consuming technologies for meeting its process heat demand.

17% of the total emission mitigation is provided by transportation sector when 10% emission constraint is identified. The biggest contribution belongs to the road transport. Total diesel consumption and total gasoline consumption decrease by 8% and 13% respectively. This decline in the use of fuel stems from the efficiency boost in the transportation sector. In BAU_20_BM and BAU_25_BM scenarios, use of vehicles running on alternative fuels becomes extensive as emission constraints get more stringent. In 2032, 60PJ worth of CNG is consumed for meeting heavy duty vehicle demand.

Hydrogen consumption is activated in 2027 under BAU_20_BM and BAU_25_BM scenarios with 1.90PJ and 4.10 PJ respectively. In 2042, this value rises to 44,53PJ after commercial truck hydrogen fuel cell becomes operational. Additionally, BAU_25_BM scenario initiates 0.0496PJ rail passenger transport (Hydrogen FC) system in 2022. Regarding electricity powered vehicles' that has car battery technology, it is initialized in 2022 with 20,54PJ and reaches 49.71PJ at the end of the planning horizon.

As maritime transportation is investigated, it is seen that the sector switches to highly efficient fuel oil using technologies (fuel inject and bubble tub) starting from 2027. Average efficiency increase in maritime sectors reaches 14% according to BAU_25_BM scenario. Airline transportation comes up with a limited response to emission constraints due to high new capacity costs. Whereas BAU_10_BM produces similar numbers to the findings of the BAU scenario, BAU_20_BM and BAU_25_BM indicate 16,5% increase in the average efficiency with a limited number of hydrogen powered aircraft technology usage.

Bound scenario emission values are given in Figure C.17. As emissions between BAU_TM and BAU_BM are different, variations are observed among 10%, 20%, and 25% emission bound scenarios. Section 6.4 explains how emission costs per reduction vary from TIMES_TR and BUEMS_TR model results.

6.3.4. System Cost

The change in the system costs are provided in Table 6.16. The cost of increased expenditures per decrease in emissions is listed in

Table 6.17. Emission reduction costs per ton which are calculated by the model turn out to be higher than the emission prices defined within the model.

Table 6.16. BUEMS model total system cost (2012 Million US $).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
BAU_BM	1217698	1887911	2157722	2557338	2833471	3915330	4918299	5459447	6056581
BAU_10_BM	1217698	1891037	2161060	2563116	2837303	3919228	4922749	5464640	6061775
BAU_20_BM	1217698	1908154	2173697	2578217	2854778	3939754	4945923	5483303	6080170
BAU_25_BM	1217698	1911320	2176376	2581439	2857788	3943317	4950449	5487305	6085831

Table 6.17. Cost of mitigation (\$/ton of CO_2).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**	**Average**
BAU_10_BM	0	68,7	62,4	89,3	53,6	43,6	40,9	38,9	32,3	53,7
BAU_20_BM	0	188,1	118,1	116,7	122,2	114,8	106,5	69,9	57,2	111,7
BAU_25_BM	0	278,3	200,3	199,2	168,4	159,4	166,4	119,9	140,8	179,1

Average emission reduction cost is calculated as $54 per ton in BAU_10_BM scenario, while this value is found for BAU_20_BM and BAU_25_BM scenarios as $112 and $179 respectively.

Bound scenario emission values are given in Table C.1 for TIMES_TR model. Average emission reduction cost is calculated as $43 per ton in BAU_10_TM scenario, while this value is found for BAU_20_TM and BAU_25_TM scenarios as $99 and $154 respectively.

6.4. MACC Analysis for Policy Instruments

Marginal abatement cost curves (MACC) are popular policy tools that have been constructed in many researches over the past 20 years. In this thesis they used to indicate emission abatement potential of specified technologies that belong to power sector and transport sector. There exist different approaches in constructing abatement cost curves. Kesicki, F., and Strachan, N. (2011) and Du *et al.*, (2015) presents two basic methodologies namely; expert-based MACC and system approach based MACC. The former requires individual assessment of abatement measures (carbon abatement potential and related costs) and each measure should be observed in isolation. The latter utilizes energy model outputs to drive MACC.

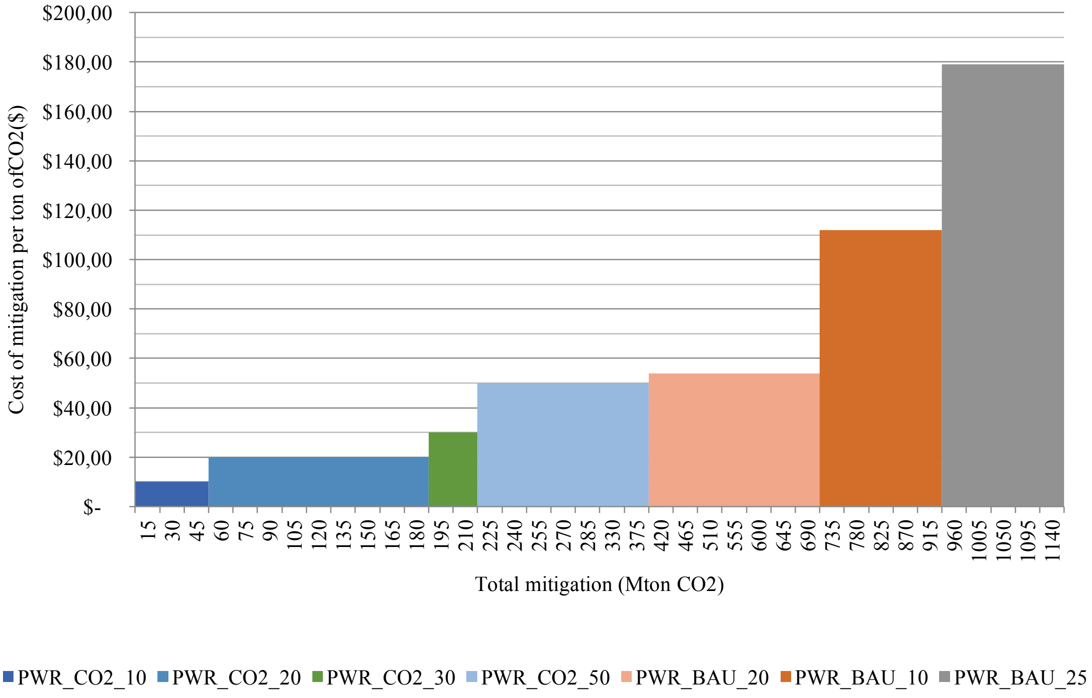


Figure 6.25. MACC for power sector.

Top-down models and bottom-up models are both eligible for this approach. A carbon tax is introduced into the model, and aggregated sector response is tracked rather than a specific technology. Chen, W. (2005) and Kesicki, F. (2013) drives MACC by utilizing the results of MARKAL model. They use the approach of setting CO_2 price to obtain the sectorial technology change in response. For this branch of models, another common way to generate it is to run the model with different strict emission limits and to derive the corresponding CO_2 prices.

In addition to the previously indicated demand side approaches, De Cara and Jayet (2011) proposed a third option called Supply-side/production-based MACC which utilizes production theory to drive it. First production possibility set determined, then by sacrificing on profit in order to mitigate the CO_2 emissions, the opportunity cost to cut emission is derived.

In this section MACC are driven by using BUEMS model results. Neither system base is preferred to gather abatement levels and related cost values in technological detail. In MACC, emission mitigation potentials of the sectors that evaluated within the scope of low carbon development pathway. MACC illustrate the marginal costs of carbon emission abatement potentials about BAU scenario results. In this section, MACC analysis is built on a sectorial basis.

For MACC analysis, the emission mitigation costs (per ton of CO_2) obtained from the aforementioned policies (including the cases of emission bound and carbon tax) that investigated in scenario analysis are taken into consideration.

Each bar presents one of the sectors (Agriculture, power, transport, residential and commercial, industry) under a specific emission scenario (BAU_10_BM, BAU_20_BM, BAU_25_BM, CO2_10_BM, CO2_20_BM, CO2_30_BM, CO2_50_BM). The width of the bar illustrated the emission mitigation potential of the considered sector about BAU scenario emission levels. Finally, the height of the bar displays the additional cost occurred for each unit of emitted CO_2. By MACC analysis the emission mitigation potential of each policy is scrutinized.

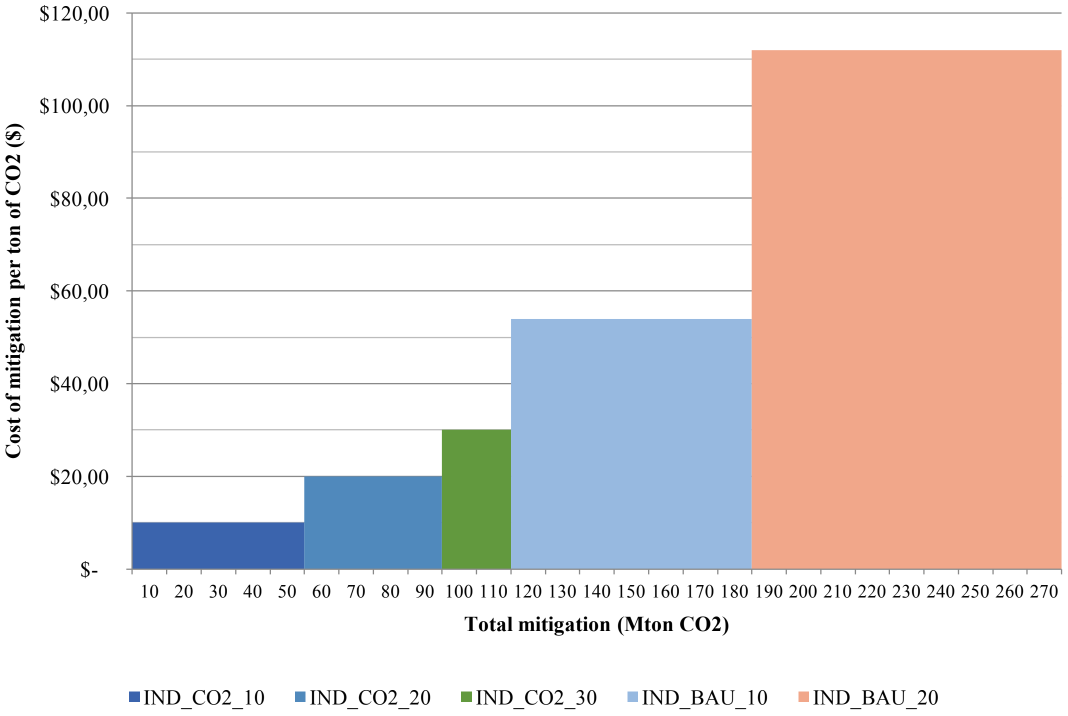


Figure 6.26. MACC for industry sector.

MACC of the power sector is presented in Figure 6.25. The power sector has a flexible structure that shows positive response under seven different scenarios. When the amount of mitigation and respective price per ton of CO_2 emitted are investigated, it is found that a reduction between 225 Mton CO_2 and 1095 Mton CO_2 is possible for this sector in the presence of emission cost which is $50 or higher. In Section 6.2 and Section 6.3, the change in the emission levels and the structure of the electricity generation regarding the fuel switches are examined in a detailed way.

MACC of power sector from TIMES_TR model is presented in Figure C.13 to compare BUEMS_TR and TIMES_TR model results. When unit reduction cost reaches $30 and above, total reduction potential changes from 262 to 1077 Mton CO2. When 25% emission constraint is added, maximum reduction of power sector is $154. This value equals to 1077 Mton CO2.

As illustrated in Figure 6.26, industry sector is the second behind power sector in terms of the level of abatement. It has a potential of reducing 180 Mton CO_2 of emission under the condition that the cost of emission mitigation is less than or equal to $120 per ton of CO_2.

Industry sector provides this reduction by switching to more efficient technologies for motor drives (MDR) and facility energy demand (FAD) except for the processes that necessitate the use of high heat treatment requiring coal.

MACC of industry sector from TIMES_TR model is presented in Figure C.14 to compare BUEMS_TR and TIMES_TR model results. When mitigation cost exceeds $40, a meaningful response from industry sectors is observed. Total reduction equals to 240 Mton CO2 with $100 mitigation cost. TIMES_TR forecasts that industry reduction will be less than 20 Mton CO2.

Residential and commercial sector activates 65% of its total reduction potential with emission costs of $85 and below. One reason for this is the fact that the durability of the residual capacity of home appliances is pretty low. For instance, there are 45 different technologies for lighting that have the probability to be engaged until 2052 and the average durability of a lightbulb is just two years. Therefore, the residential and commercial sector can easily reduce its amount of consumption with a low tax.

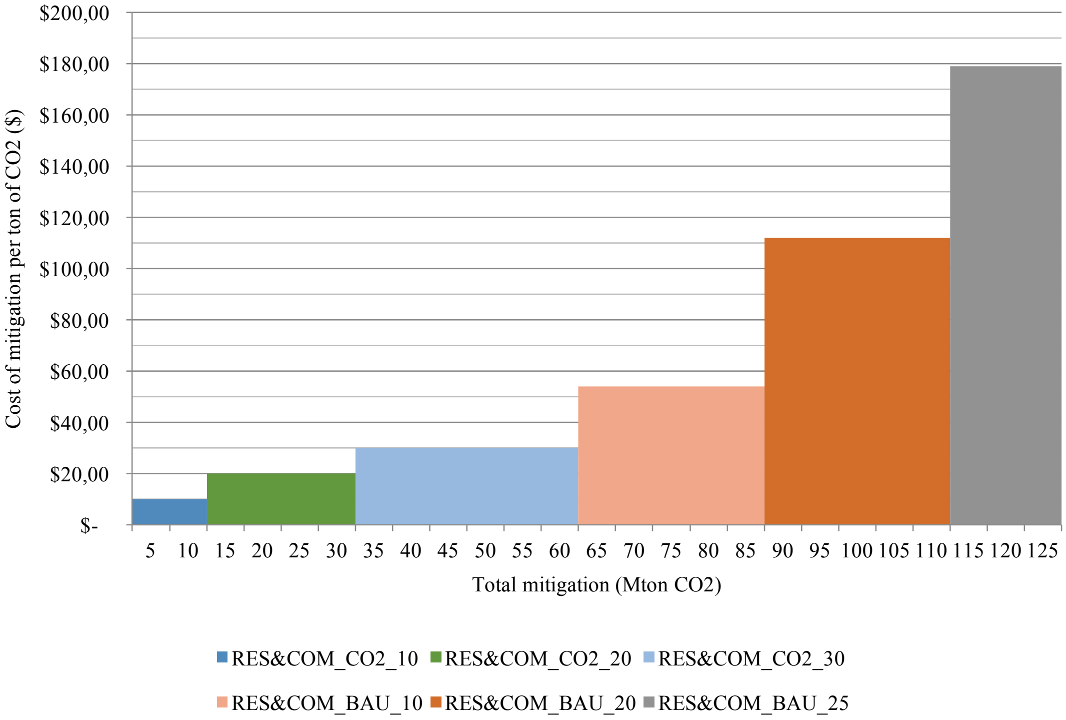


Figure 6.27. MACC for residential and commercial sector.

To compare the BUEMS_TR and TIMES_TR model results, MACC of industry sector derived from TIMES_TR model is presented in Figure C.15. Both models calculate reduction capacity similarly but the costs are different. This sector has 88 Mton CO2 reduction potential for $50 tax in TIMES_TR model. This value reaches 145 Mton CO2 with $154 emission mitigation cost.

In the BUEMS model, the average life of a vehicle ranges from 12 to 20 years depending on the type of transport (air, rail, marine and road). Due to the fact that new capacity installments require large investments and even become costlier to the system through high residual capacity, transport sector shows inadequate responsive to low emission taxes.

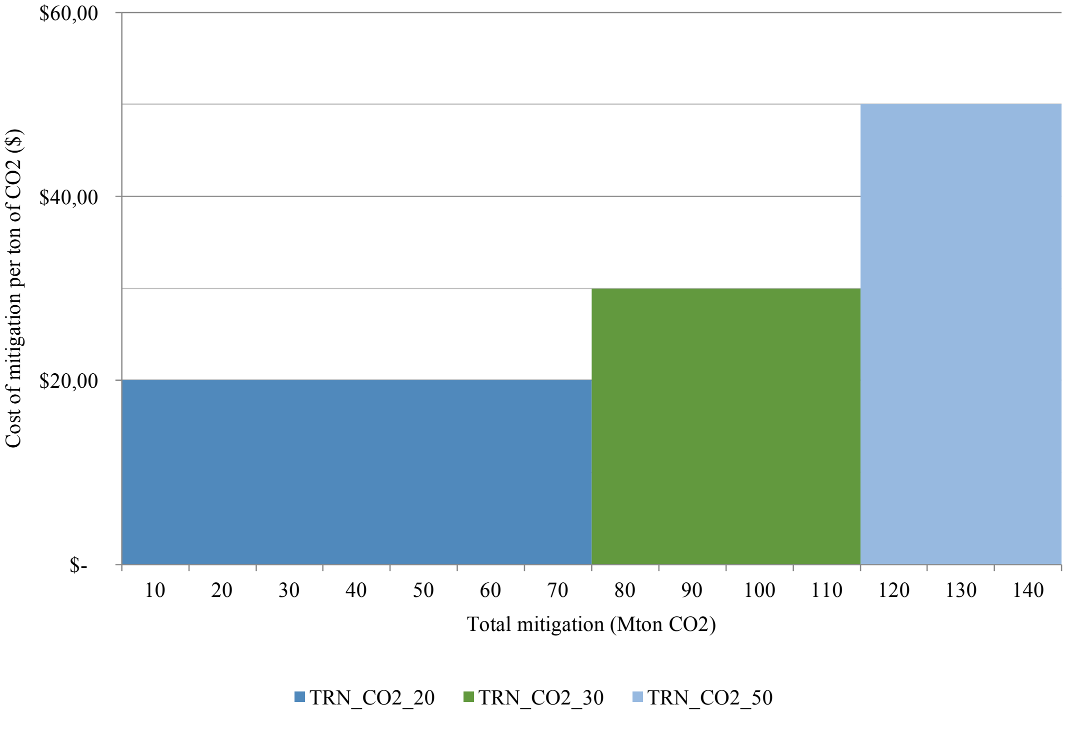


Figure 6.28. MACC for transport sector.

“Carbon tax” scenarios are observed to be more effective in the transportation sector as illustrated in Figure 6.28. As total emissions are restricted in emission bound scenarios, sectors with a higher reduction potential (for lower costs) account for the most of the reduction. Hence, inflexible sectors such as transportation sector do not provide high emission reduction. However, equal additional costs are identified for each sector under a carbon tax. Using fuels with high emission rates such as diesel gasoline jet fuel, transportation sector makes more reduction in comparison with emission bound scenarios.

MACC of industry sector derived from TIMES_TR model is presented in Figure C.16 in order to compare BUEMS_TR and TIMES_TR model results. In BUEMS_TR model, total mitigation potential is 140 Mton CO2, while this value reaches 225 Mton CO2 in TIMES_TR model, with mitigation cost equals to $154.

The reaction of Transport sector about emission mitigations scenario are described in Sections 6.1.4 and 6.2.3.

6.5. The Analysis of Supply Shock

The structure of the BUEMS model enables evaluation of investment projects that supply primary fuel into the model. By this way, it is possible to analyze the effect of the supply investments on the considered energy system numerically. Trans Anatolian Natural Gas Project “TANAP” that has a strategic importance is selected as a case to test the supply shock effect on Turkish Energy System.

The Intergovernmental Agreement was signed in Istanbul on June 26, 2012. The main objective of TANAP is to contribute to both Turkey and Europe’s energy supply security. When we look at the Turkey’s energy figures, it is apparent that the demand for natural gas has a sharp spike. Estimates of gas volumes demanded by Turkey is expected to increase dramatically from now on.

Indeed, Turkey’s natural gas consumption has increased to 48.6 billion cubic meters from 22.1billion cubic meters between 2004-2014 period (BP, 2015).

TANAP is planned to be concluded in 2018, therefore it will be assigned as a usable resource from 2018. Planned installation cost is announced as 10-11 billion US$. The planned capacity of the pipeline would be 16 billion cubic meters (570 billion cubic feet) of natural gas per year at initial stage and would be increased later up to 23 billion cubic meters

(810 billion cubic feet) by 2023, 31 billion cubic meters (1.1 trillion cubic feet) by 2026 (Ozdemir *et al.*, 2015).

According to Head of the State Oil Company of Azerbaijan Republic (SOCAR) Rovnag Abdullayev, TANAP is expected to decrease by 25% on natural gas cost estimates (Turkey is paying Iran 570 US$/$m^3$, Russia 500 US$/m^3, Azerbaijan only 380 US$/$m^3$ for natural gas) (Natural Gas Europe, 2015). It is assumed that the effect of this discount that will happen in supply shock is directly reflected in end-use demand.

It is obvious that, Turkey requires additional resources to meet the constantly increasing natural gas demand. In this respect, Turkey will be able to able to meet a substantial portion of her natural gas needs by buying 6 million m^3 natural gas from TANAP starting from 2018.

Natural gas is the major energy fuel for Turkey. Turkey's total energy consumption is composed of 35% natural gas, 29% coal, and 27% petroleum. Natural gas is mainly used for generating electricity. In 2014, 49% of natural consumption was for electricity production, while 26% for industry, and only 19% for residential use. Almost all natural gas consumed is imported, sustainability and procurement at an economic price have become one of national strategic goals. In this context, TANAP is important for Turkey.

54,76% of total natural gas is imported from Russia, 18,13% from Iran, and 12,33% from Azerbaijan. Even though an excessive dependency exists to Russia and Iran; a very high price is paid for natural gas. When we consider that Azerbaijan is offering the cheapest price, additional supply from there will also increase the bargaining power of Turkey over other suppliers. Table 6.18, shows the change in emission values as natural gas supply increases and prices decrease.

Table 6.18. Change in total emissions under supply shock (MTon CO_2).

Mton CO_2	**2012**	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
BAU_TM	348	459	540	652	721	901	1097	1345	1619
SS	348	441	518	633	687	848	1044	1270	1543

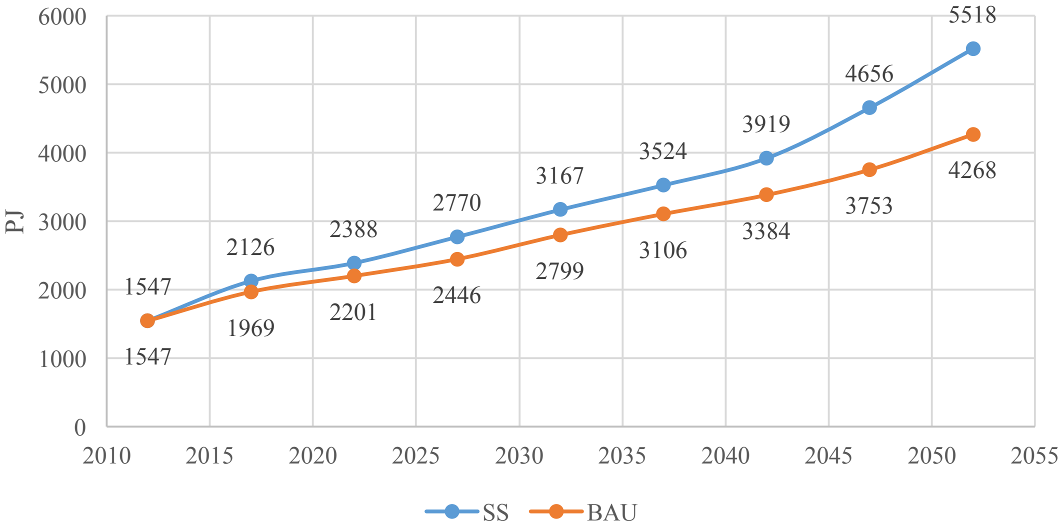


Figure 6.29. Natural gas consumption under SS and BAU (PJ).

While BAU scenario results in 7683 Mton CO_2 emission, by the activation of TANAP (decreasing the natural gas prices by 30%) total emissions is expected to be 7332 Mton CO_2. The assumptions are the same for both scenarios. Hence, the isolated effect of change in natural gas prices on the system could be observed. TANAP alone achieves a 5% reduction in greenhouse gas emissions level for Turkey. When the fuel consumptions are investigated, it is observed that Turkey's natural gas consumption increased from 833PJ value in 2004 to 1829PJ in 2014, an obvious increase in natural gas consumption. Figure 6.29 shows how these values differ under TANAP and under BAU scenario. Change in natural gas prices caused a 16% increase in total demand. Change in demand with respect to each sector is given in Table 6.19. Due to this increase in natural gas consumption, total hard coal consumption decreases by 10% (2246PJ), lignite consumption decreases by 14,7% (2514PJ) during the 2012-2052 period. With this analysis, TANAP's benefits to Turkish Energy Market are revealed.

Table 6.19. Change in total natural gas consumption (PJ).

	2012	**2017**	**2022**	**2027**	**2032**	**2037**	**2042**	**2047**	**2052**
Industry	0,0	33,7	58,1	136,2	195,7	244,8	242,5	332,2	570,7
Power	8,0	128,7	135,3	145,7	177,6	177,6	177,6	177,6	177,6
Res. and Com.	0,0	0,0	0,0	0,0	0,0	0,0	114,9	394,3	502,5

7. CONCLUSION

In this thesis, the main goal is to satisfy the need for a model that can represent the energy sector in Turkey, and its unique characteristics. This model aims to provide reliable and realistic results that can represent how system would respond to any actions that the policy makers will implement.

Turkey, just like any nation that is involved in war against global warming, is expected to take action. It is obvious that a national model guiding policy makers in strategic decisions is needed. BUEMS is built to satisfy this need. While BUEMS is modelling the Turkish Energy System in detail, it makes it more comprehensible through open model formulation. As it requires less information when compared to its counterparts, it provides a more convenient modelling structure. With its flexible structure, it enables any additional analyses as well as scenario analyses. It provides all these advantages through bottom-up perspective which is technologically high detailed.

The BUEMS model attempts to determine the supply of the primary energy resources (energy trade option is also available) accompanied by investment and operating that constitutes an energy system to meet the useful energy demands over the pre-specified time horizon at minimum cost.

BUEMS attempts to obtain an optimizing solution to the described problem by applying linear programming methodology. The model comes up with an optimal system configuration that meets energy demands over a set of constraints at least cost at each period. The developed model has a straightforward structure that allows the evaluation of energy sector as a whole with an open structured framework (it provides all the formulations to represents the relationships of the underlying mechanism).

BUEMS model provides a range of energy system configurations for Turkey that will deliver projected energy demand requirements optimized to least cost and subject to a range of policy constraints for the period out to 2052. After the results of the BUEMS model are validated by the outcomes of TIMES_TR model, a policy family of tax and emission bound applications to mitigate greenhouse gas emissions are investigated.

Tax on carbon is introduced into the model in four penalty levels ($10, $20, $30 and $50 cases) and emission bound is set in three different grades as 10%, 20% and 25% reduction on emissions with respect to the total CO_2 levels that belong to BAU scenario.

Under BAU scenario, total emissions are expected to reach approximately 1607Mton CO_2 by 2052 owing to the growth in end-use energy demand. For the base year, Power Sector was responsible for 36,3% of total emissions, and will continue to be the main reason with 38,1% share in 2032 and 46,6% by 2052. It is seen that natural gas is the dominant source of energy for the demand side, whereas for electricity generation, coal leads the sector with the 1370PJ of lignite consumption and 651PJ of hard coal by 2052. If there exist no additional costs on greenhouse gas emissions, coal strengthens its position with the largest consumption value due to its comparatively low prices.

In this thesis, extensive range of emission mitigation scenario analysis is evaluated to provide analytical insights on the system behavior of Turkish Energy System.

The principal finding is that; 57% of emission mitigation under BAU_25_BM entails the change in the fuel type and electricity generation infrastructure. Dramatic cut on CO_2 emissions requires high marginal prices with the estimate of $179 under the scenario that requires sharp emission decline. Despite to the fact that penetration of renewables is limited under BAU scenario, total electricity generated by renewables is anticipated to reach 159.4TWh under 25% emission bounds. Geothermal and solar power is favored as a higher limitation on total emission is set. Onshore wind turbine technology and nuclear power plants are the two of most attractive investment opportunities regarding their unit abatement cost scores.

An absolute 25% reduction in CO_2 emissions imposes new technological investments that change the behavior of the system drastically not only electricity generation but also all of the demand sectors undergoing significant changes. Hydrogen gets on the stage as higher emission restriction is imposed by the model. All of the hydrogen production is utilized by the transport sector. Due to technological change, the consumption of refined oil is reduced significantly. As a result of the aforementioned issues, 13% of the total emission savings are provided by the transport sector. Industry sector also changes its energy consumption on machine drives and facility drastically by the installation of technologies with high-efficiency rates. In general, for the emission bound scenario, advances in overall technology efficiencies are substantial.

An analysis of the impacts on the national scale, four level carbon tax scenarios for \$10, \$20, \$30 and \$50 has been carried out. Overall mitigation values reveal that the tax of \$10 is appeared to be an ineffective option. It is also not sufficient to put better emission mitigation options into service under \$20 emission tax. The abatement response starts with \$30 and peaks with \$50 case. Under CO2_50_BM scenario Turkish energy system is anticipated to reduce 14% of total emissions with the existence of a pervasive change of efficiency throughout the planning horizon.

Regardless of the type of policy that discourages CO_2 emissions, total mitigation level is mainly related to power and industry sectors.

Under both emissions bound and tax scenarios, the transport sector is anticipated to be the strictest sector and has the least contribution on emission mitigation after agriculture. In general, for the emission mitigation scenarios, the power sector is expected to be the primary source of reductions in total CO_2. The type of the policy instrument only changes the portfolio of electricity generation.

Residential and commercial sector provides moderate contribution on emission mitigation regardless of the scenario type

To reiterate a key point, in the absence of a strict emission bound (only excising a carbon tax into the model) the system lacks abatement by comparison with the amount of emission mitigation provided by bound scenarios. In other words, under emission tax, it is left to the optimization process to decide whether to reduce CO_2 emissions (by opting for more expensive but less-emitting technologies) or to accept a higher level of emissions and bear the associated cost (penalty) rather than to gain absolute reduction.

As mentioned before, BUEMS modeling is open to additional analyses. In the context of this thesis model is developed for a single region, covering only Turkish Energy Sector. Turkey is seen as a potential energy hub of the future between east-west and north-south corridors. As a future study, creating a multi-region model with the inclusion of neighboring countries can lead to interesting analyses that will help determine Turkey’s position in near future.

Surely, the fight against climate change still has a long way to go. This thesis is completed with the intention of providing scientific support for the fight to preserve and protect our one and only home, planet Earth.

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APPENDIX A: ENERGY MODELING LITERATURE

Table A.1. Energy-Economy-Environment modeling literature.

Name	Year	Developer	Methodology			Geographic Scale				Time			Underlying Methodology						
			Top down	Bottom up	Hybrid	National	EU	Global	Regional	Short (5)	Med. (5-15)	Long (15)	IO	IAM	CGE/AGE	Econometric Models	Simulation	Optimization	Accounting
AIM Asian-Pacific Integrated Model	1991	National Inst. For Environmental Studies Japan				✔		✔		✔				✔	✔				
BESOM Brookhaven Energy System Optimization Model	1975	Brookhaven National Laboratory Germany		✔		✔						✔						✔	
CASM the Coordinated Abatement Strategies Model	1991	The Stockholm Environment Institute																	
CETA Clean Energy Technology Association Model	1992	Electric Power Research Institute	✔					✔						✔					
CIMS Canadian Integrated Modelling System		Simon Fraser University			✔			✔			✔	✔			✔		✔		
DICE Dynamic, Integrated Climate and Economics model	1994	Yale Uni.	✔					✔			✔			✔					
E3ME Energy-Environment-Economy (E3) Model	JOULE I-II	European Commission	✔				✔			✔	✔	✔				✔			
EFFECT Energy Forecasting Framework and Emissions Consensus Tool	?	World Bank		✔					✔			✔							
EFOM ENV Energy Flow Optimization Model-ENVronment	1992	the Commission of European Communities DGXII		✔		✔					✔	✔						✔	
EFOM Energy Flow Optimization Model	1970	"Institut Economique et Juridique de l'Energie" at Grenoble, France		✔		✔					✔	✔						✔	

Table A.1. Energy-Economy-Environment modeling literature (cont.)

Name	Year	Developer	Methodology			Geographic Scale				Time			Underlying Methodology						
			Top down	Bottom up	Hybrid	National	EU	Global	Regional	Short (5)	Med. (5-15)	Long (15)	IO	IAM	CGE/AGE	Econometric Models	Simulation	Optimization	Accounting
ENERPLAN	1984	Tokyo Energy Analysis Group for UNDP		✔		✔				✔	✔						✔		
ENPEP Energy and Power Evaluation Program	1997	Argonne National Labtatory		✔		✔				✔	✔	✔					✔		
EPPA Emissions Prediction and Policy Analysis Model	1992	MIT	✔					✔	✔			✔			✔				
ERIS Energy Research and Investment Strategies Model	1998	Paul Scherrer Institute (PSI) in Switzerland		✔					✔			✔						✔	
ESCAPE the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions	1990	European Commission DGXI	✔				✔		✔	✔				✔					
ETA Macro a model for Energy Technology Assesment	1977	Stanford U.			✔							✔			✔			✔	
FUND Climate Framework for Uncertainty Negotiation and Distribution	1996	Vrije Universiteit Amsterdam	✔						✔	✔	✔	✔		✔					
GCAM Global Change Assessment Model	1997	Joint Global Change Research Instiitue, PNNL, College Park, MD)	✔						✔	✔	✔			✔					
G-CUBED A Multi-Sector Intertemporal General Equilibrium Model	1995	The Brookings Institution	✔						✔			✔			✔			✔	
GEM- E3 Global Energy Model	1995	European Commission	✔				✔				✔	✔			✔				
GREEN The GeneRal Equilibrium Environmental Model	1992	OECD	✔						✔						✔				
GTAP-Eenergy Environmental version of Global Trade Analysis Project	1993	Purdue University	✔					✔				✔			✔				

Table A.1. Energy-Economy-Environment modeling literature (cont.)

Name	Year	Developer	Methodology			Geographic Scale				Time			Underlying Methodology						
			Top down	Bottom up	Hybrid	National	EU	Global	Regional	Short (5)	Med. (5-15)	Long (15)	IO	IAM	CGE/AGE	Econometric Models	Simulation	Optimization	Accounting
HERMES Harmonized European Research for A Multinational Economic and Energy System Model	1981	European Commission	✔				✔			✔	✔				✔				
ICAM Integrated Climate Assessment Model	1998	Carniegie-Mellon University	✔						✔			✔		✔			✔		
IMAGE Energy-Industry System Model	1990	PBL Netherlands Environmental Assesment Agency, Bildhoven	✔						✔					✔					
ISEEM Industrial Sector Energy Efficiency Modeling	2012	Lawrence Berkeley National Laboratory		✔		✔			✔	✔								✔	
LEAP Long-Range Energy Alternatives Planning System Model	?	Stockholm Environment Institute		✔		✔		✔	✔		✔	✔							✔
MAED Model for Analysis of Energy Demand	1977	the University of Grenoble, France, International Atomic Energy Agency's (IAEA)		✔				✔	✔		✔	✔							✔
MARKAL Market Allocation Model	1979	ETSAP IEA, German Research Institute, Brookhaven National Laboratory		✔		✔	✔				✔	✔						✔	
MDM (UK) Multisectoral Dynamic Model	1999	Cambridge U.	✔			✔					✔	✔				✔			
MEPA Massachusetts Environmental Policy Act Model	1977	Massachusetts EEA	✔			✔			✔	✔	✔	✔	✔						
MERGE A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies	1995	Stanford U.			✔			✔	✔			✔			✔			✔	
MESSAGE Model For Energy Supply Systems And Their General Environment	1980	International Institute for Applied Systems Analysis (IIASA)		✔		✔		✔			✔	✔		✔				✔	
MESSAGE MACRO Model For Energy Supply Systems And Their General Environment	2002	International Institute for Applied Systems Analysis (IIASA)			✔	✔		✔				✔	✔					✔	

Table A.1. Energy-Economy-Environment modeling literature (cont.)

Name	Year	Developer	Methodology			Geographic Scale				Time			Underlying Methodology						
			Top down	Bottom up	Hybrid	National	EU	Global	Regional	Short (5)	Med. (5-15)	Long (15)	IO	IAM	CGE/AGE	Econometric Models	Simulation	Optimization	Accounting
MICRO-MELODIE Un Modele Energetique de Long Term Pour L'economie Française	1987	CEA, France	✔			✔					✔	✔				✔			
MIDAS Multinational Integrated Demand and Supply Model	1988	M.S. Gerber and Associates (EPRI)		✔		✔	✔					✔					✔	✔	
MINICAM Mini-Climate Assessment Model	1996	Pacific Northwest National Laboratory	✔						✔			✔		✔					
NEMS National Energy Modeling System of USA	1994	U.S. Department of Energy							✔			✔			✔		✔		
NIA National Impact Analysis Model	2004	U.S. Department of Energy		✔															✔
ORANI-G	1977	Monash University	✔			✔				✔					✔				
PAGE (Policy Analysis of The Greenhouse Effect)	1993	University of Cambridge	✔						✔					✔					
PAMS Policy Analysis Modeling System	1999	Lawrence Berkeley National Laboratory		✔		✔													✔
POLES Prospective Outlook on Long-Term Energy Systems Model	JOULE I-II	European Commission			✔	✔		✔	✔			✔				✔	✔		
PRIMES PRice Inducing Model of the Energy System	JOULE I-II	European Commission (National Technical U. Of Athens)		✔		✔	✔		✔			✔						✔	
QUEST A Macro-econometric Model for EU Countries	1988	European Commission DGII	✔				✔			✔	✔					✔			
RAINS model of the International Institute for Applied Systems Analysis (IIASA)	1990	International Institute for Applied Systems Analysis (IIASA)																	

Table A.1. Energy-Economy-Environment modeling literature (cont.)

Name	Year	Developer	Methodology			Geographic Scale				Time			Underlying Methodology					
			Top down	Bottom up	Hybrid	National	EU	Global	Regional	Short (5)	Med. (5-15)	Long (15)	IO	IAM	CGE/AGE	Econometric Models	Simulation	Optimization	Accounting
REEPS Residential End-Use Energy Planning System	1992	lectric Power Research Institute		✔					✔								✔		
RESGEN Resource Generation		Resource Management Associates		✔		✔												✔	
RETscreen Renewable Energy Project Analysis Software	1998	Natural Resources Canada		✔		✔				✔	✔	✔							
RICE Regional Integrated Model of Climate and the Economy	1992	Yale University, MIT	✔						✔					✔				✔	
SCREEN Hybrid Bottom-Up Computable General Equilibrium Model	1993	Fisher *et al.*			✔	✔									✔			✔	
SGM Second Generation Model	2003	PNL Pacific Northwest National Laboratory	✔						✔	✔					✔				
SLICE Stochastic Leaarning Integrated Model of Climate Change	1994	University of California.	✔					✔						✔					
TIMES The Integrated MARKAL-EFOM System	1997	IEA		✔		✔		✔	✔			✔						✔	
WARM World Assesment of Resource Management	JOULE I-II	European Commission	✔				✔				✔					✔	✔		
WEM World Energy Model	1993	IEA			✔				✔		✔	✔			✔				
WIAGEM World Integrated Assessment General Equilibrium Model	2002	University of Oldenburg,	✔						✔			✔			✔				
WORLDSCAN	2006	CPB	✔						✔			✔			✔	✔			

APPENDIX B: ENERGY BALANCE

Table B.1. Energy Balance Sheet.

	Hrd Coal	Lignite	Asphalt	Coke	P. Coke	Wood	Animal and Agr. R.	T.S.F.	Oil	Natural Gas	Hydro Power	Geo.	Biofuels	Wind	Elc.	Jeo.H. and OthH.	Solar	TOTAL
Domestic Production (+)	1095	15355	567	0	0	2350	1115	20483	2440	533	4976	773	23	504	0	1463	768	31964
Importation (+)	19237	0	0	253	2936	0	0	22426	37856	37910	0	0	0	0	501	0	0	98693
Exportation (-)	5	0	0	0	0	0	0	5	6103	504	0	0	0	0	254	0	0	6866
Primary Energy Supply	20316	15433	471	275	2800	2350	1115	42761	31205	37373	4976	773	23	504	247	1463	768	120093
Conversion and Energy Sector	-11018	-10066	-219	2743	0	-5	-60	-18626	-3744	-20105	-4976	-773	0	-504	16418	1225	0	-31086
Electric Power Plants	-6922	-10023	-219	0	0	-5	-60	-17229	-753	-19049	-4976	-773	0	-504	20597	1225	0	-21463
Coking Plant	-4085	0	0	2743	0	0	0	-1342	0	0	0	0	0	0	0	0	0	-1342
Petroleum Refineries	0	0	0	0	0	0	0	0	-1018	-1042	0	0	0	0	-99	0	0	-2158
Internal Consumption and Loss	-11	-43	0	0	0	0	0	-55	-202	-14	0	0	0	0	-4080	0	0	-4351
Total Energy Consumption	9297	5367	252	3018	2800	2345	1055	24134	27461	17268	0	0	23	0	16665	2688	768	89007
Sectorial Total	9297	5367	252	3018	2800	2345	1055	24134	27461	17268	0	0	23	0	16665	2688	768	89007
Industrial Consumption	2574	2327	144	3018	2800	0	0	10863	1920	8079	0	0	0	0	8013	1225	268	30368
Food	56	11	0	2	0	0	0	69	16	440	0	0	0	0	503	0	0	1028
Textile	46	90	0	0	0	0	0	136	38	513	0	0	0	0	1248	0	0	1935
Paper	3	74	0	0	0	0	0	77	43	123	0	0	0	0	151	0	0	393
Ceramic	58	144	0	0	24	0	0	226	176	610	0	0	0	0	94	0	0	1106
Glass	0	0	0	0	0	0	0	0	34	253	0	0	0	0	83	0	0	371
Chemical-Petrochemical	83	88	0	41	0	0	0	212	444	709	0	0	0	0	441	0	0	1806
Fertilizer	0	0	0	0	0	0	0	0	6	655	0	0	0	0	27	0	0	688
Cement	1452	1371	0	2	2170	0	0	4994	37	139	0	0	0	0	600	0	0	5771
Iron and Steel	833	28	0	2940	136	0	0	3938	48	832	0	0	0	0	1761	126	0	6705
Non-ferrous Metals	11	55	0	0	0	0	0	66	11	462	0	0	0	0	207	0	0	746
Other	24	238	144	0	470	0	0	876	993	3012	0	0	0	0	2785	1100	268	9033
Transportation	0	0	0	0	0	0	0	0	20359	341	0	0	23	0	73	0	0	20796
Rail Transport	0	0	0	0	0	0	0	0	143	0	0	0	0	0	23	0	0	166
Sea Transport	0	0	0	0	0	0	0	0	528	0	0	0	0	0	0	0	0	528
Air Transport	0	0	0	0	0	0	0	0	1258	0	0	0	0	0	0	0	0	1258
Road Transport	0	0	0	0	0	0	0	0	18429	62	0	0	23	0	28	0	0	18543
Other Sectors	6724	3040	108	0	0	2195	211	12277	1787	8848	0	0	0	0	8579	1463	500	33453
Residential and Commercial	6662	3040	108	0	0	2195	211	12215	804	8833	0	0	0	0	8076	1081	500	31509
Agricultural	62	0	0	0	0	0	0	62	983	14	0	0	0	0	503	382	0	1944
Feedstock	0	0	0	0	0	150	844	994	3396	0	0	0	0	0	0	0	0	4390

APPENDIX C: TIMES MODEL RESULTS

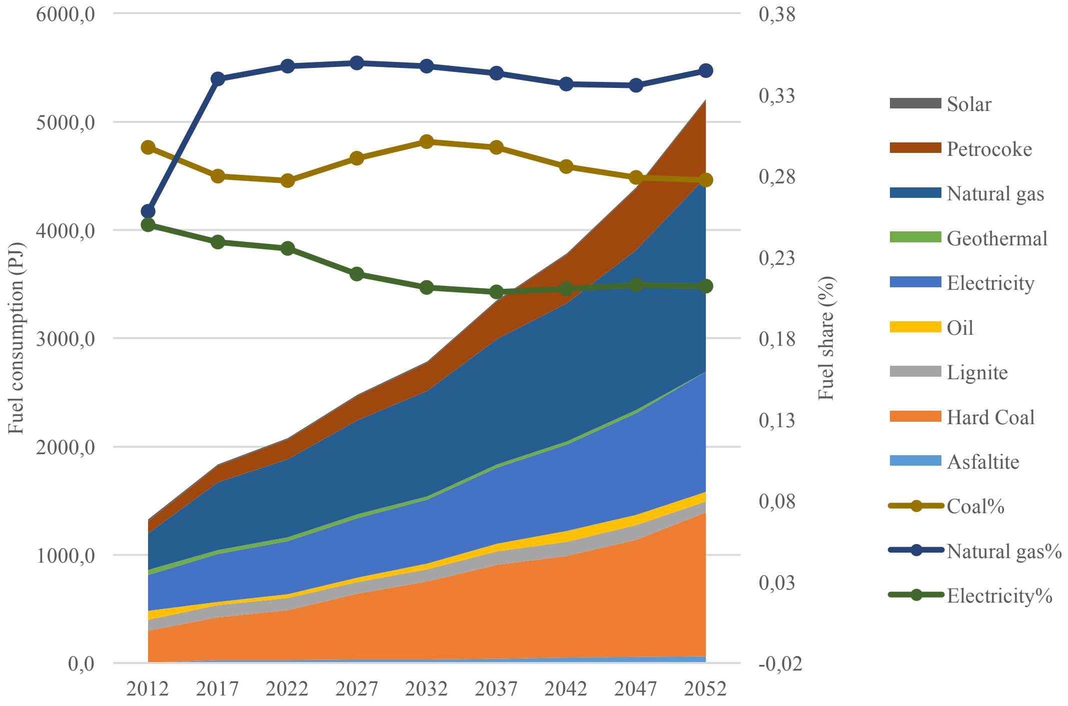

Figure C.1. Industry sector fuel consumptions under BAU_TM(PJ).

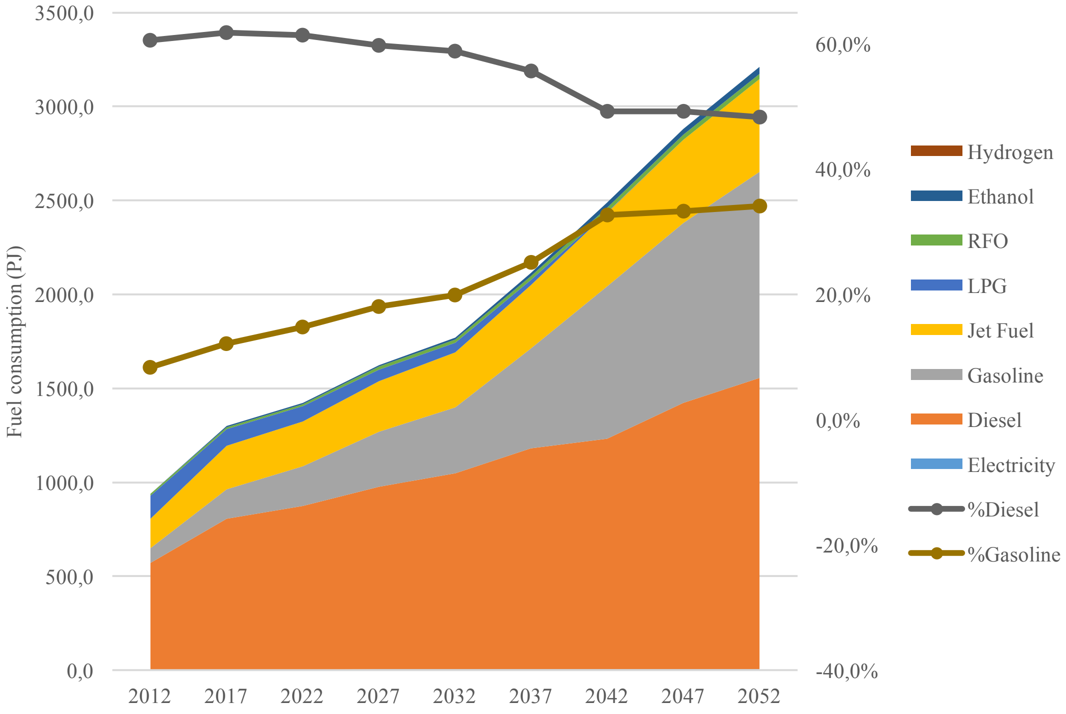

Figure C.2. Transport sector fuel consumptions under BAU_TM(PJ).

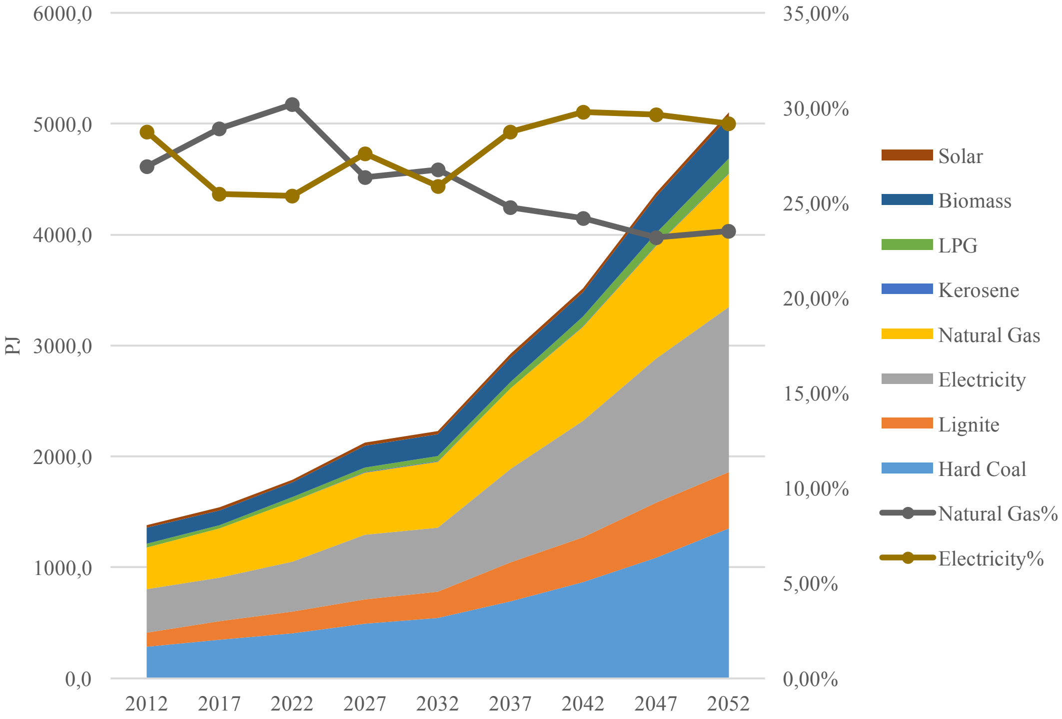

Figure C.3. RES and COM sector fuel consumptions under BAU_TM(PJ).

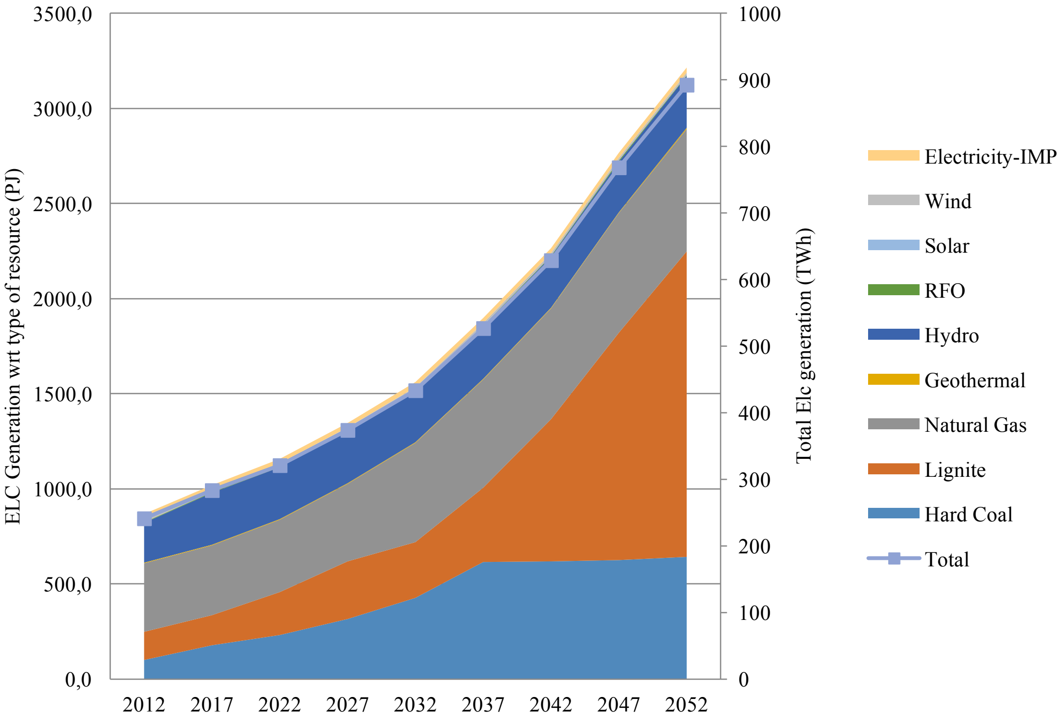

Figure C.4. Electricity generation wrt fuel type under BAU_TM(PJ).

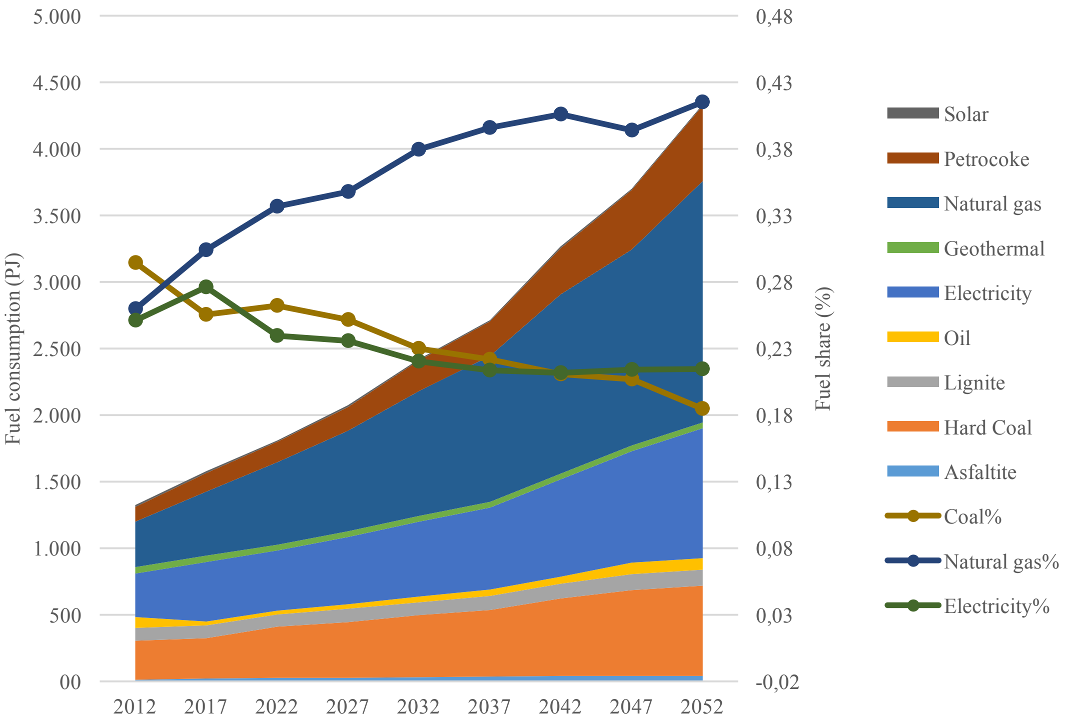

Figure C.5. Industry sector fuel consumptions under CO2_50_TM (PJ).

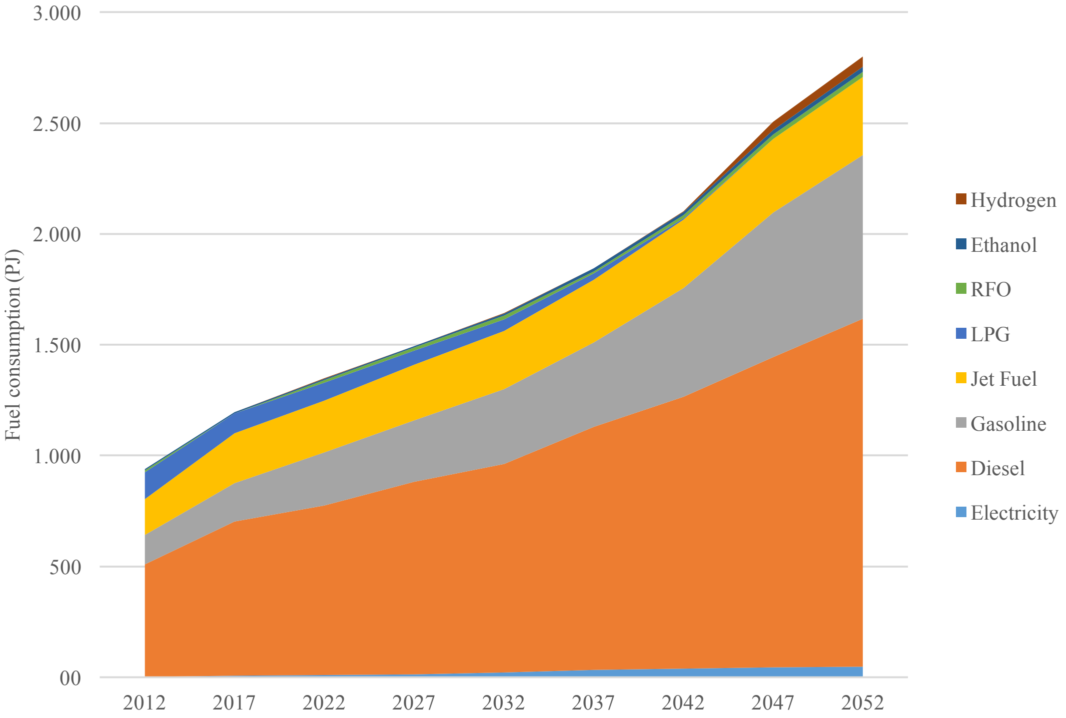

Figure C.6. Transport sector fuel consumptions under CO2_50_TM (PJ).

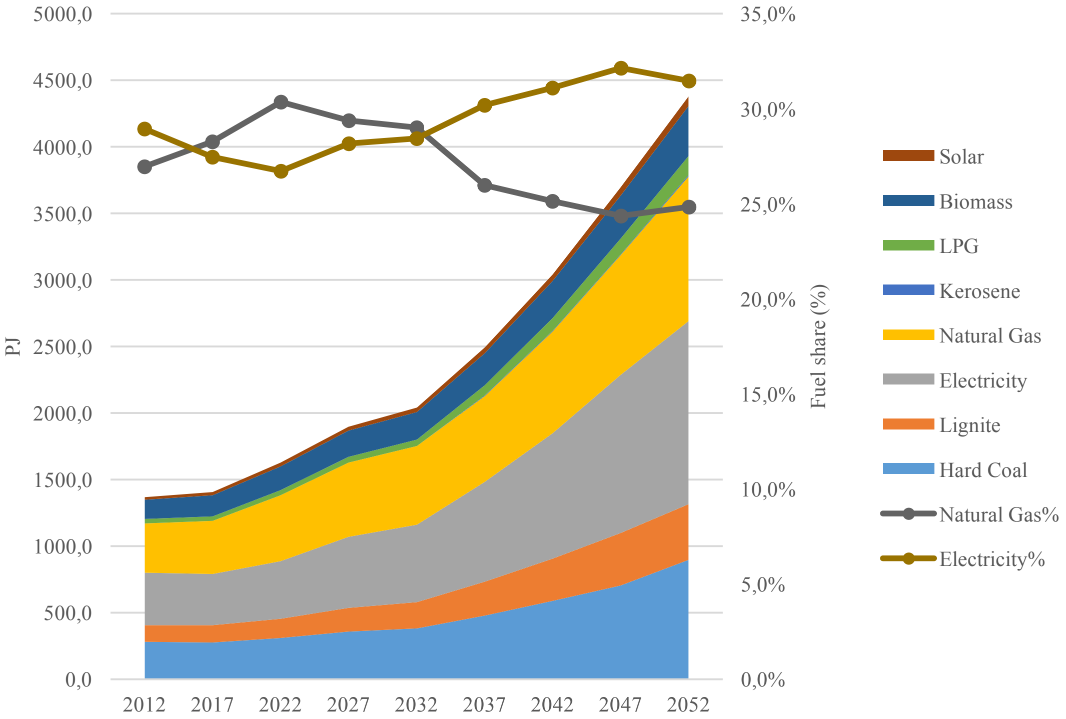

Figure C.7. RES and COM sector fuel consumptions under CO2_50_TM (PJ).

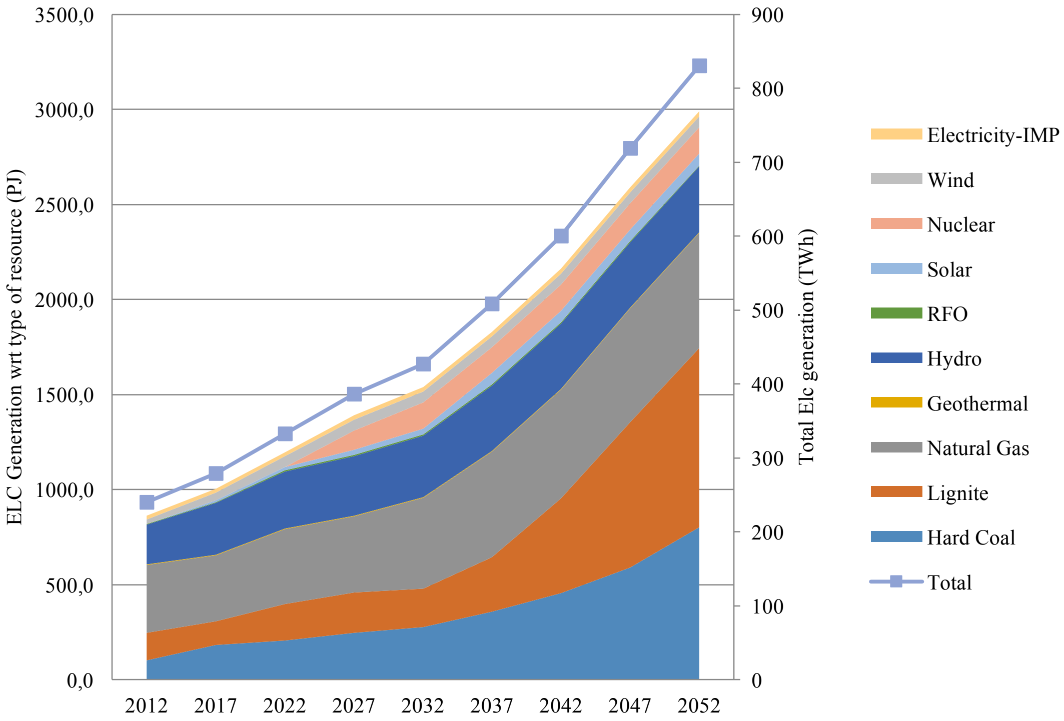

Figure C.8. Electricity generation wrt fuel type under CO2_50_TM (PJ).

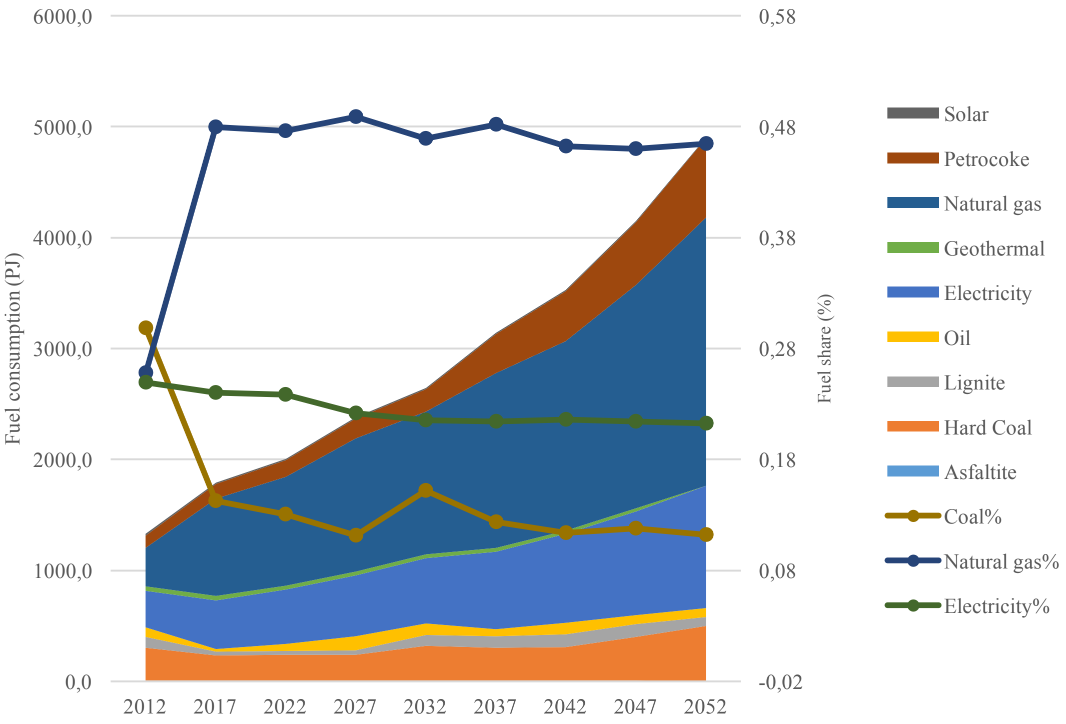

Figure C.9. Industry sector fuel consumptions under BAU_25_TM (PJ).

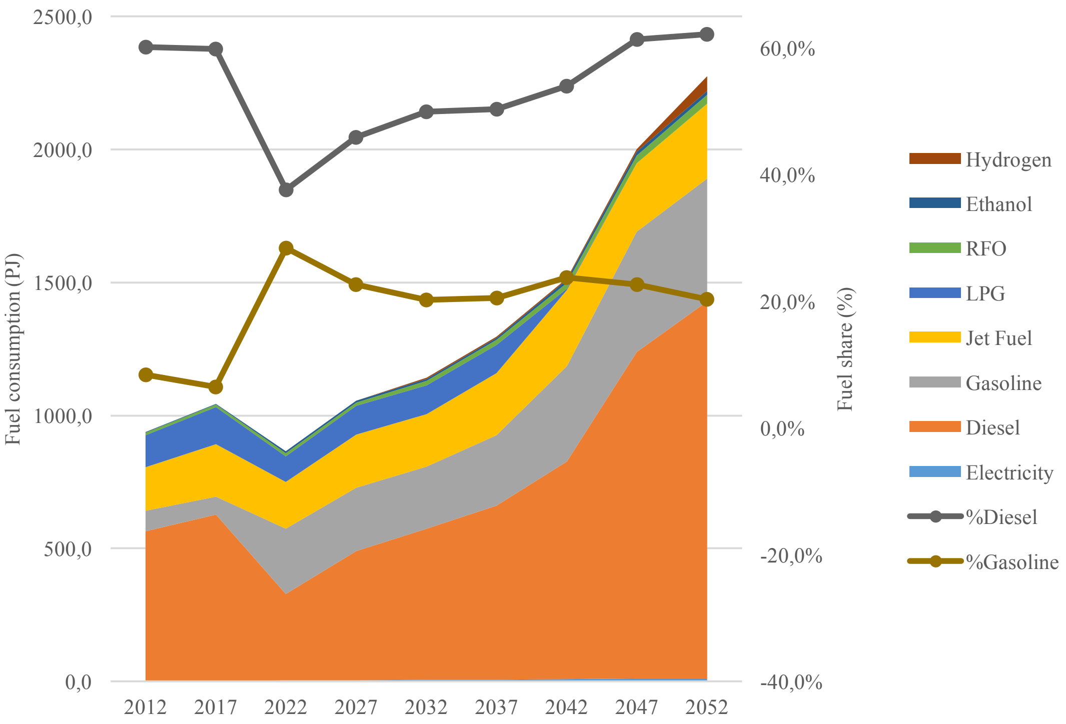

Figure C.10. Transport sector fuel consumptions under BAU_25_TM (PJ).

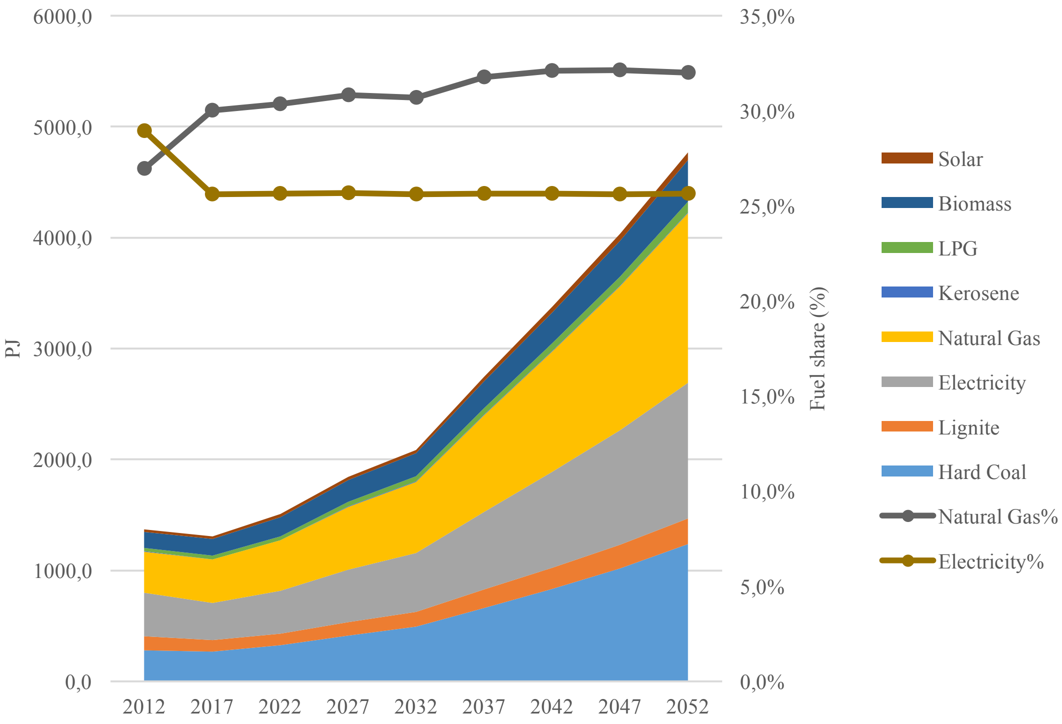

Figure C.11. RES and COM sector fuel consumptions under BAU_25_TM (PJ).

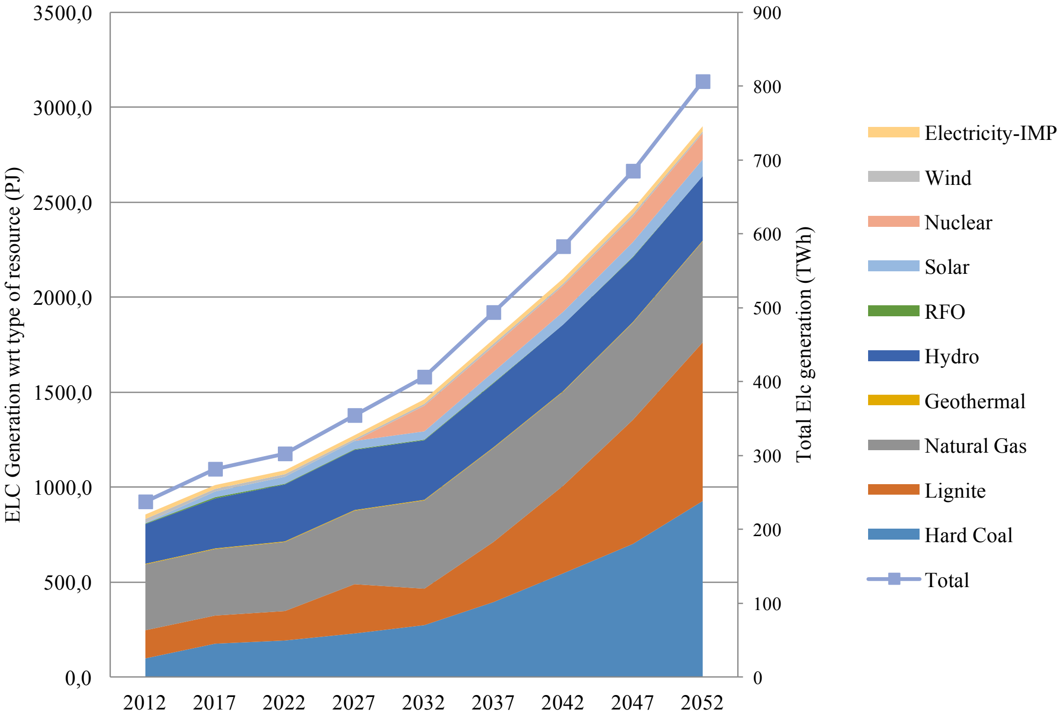

Figure C.12. Electricity generation wrt fuel type under BAU_25_TM (PJ).

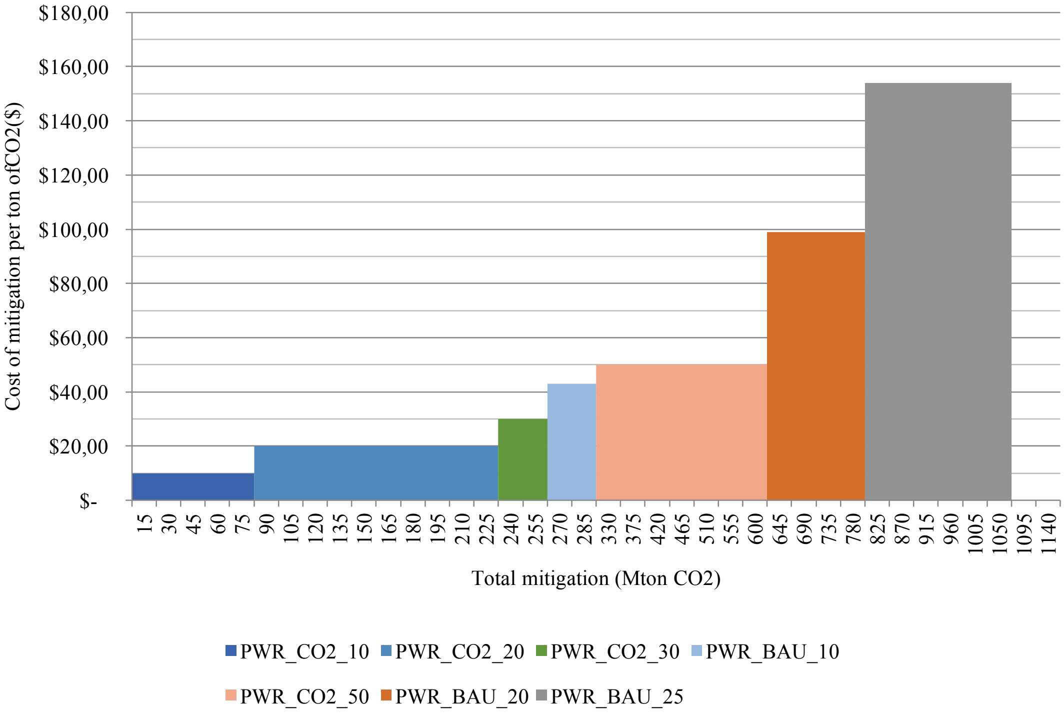

Figure C.13. MACC for power sector under TIMES_TR.

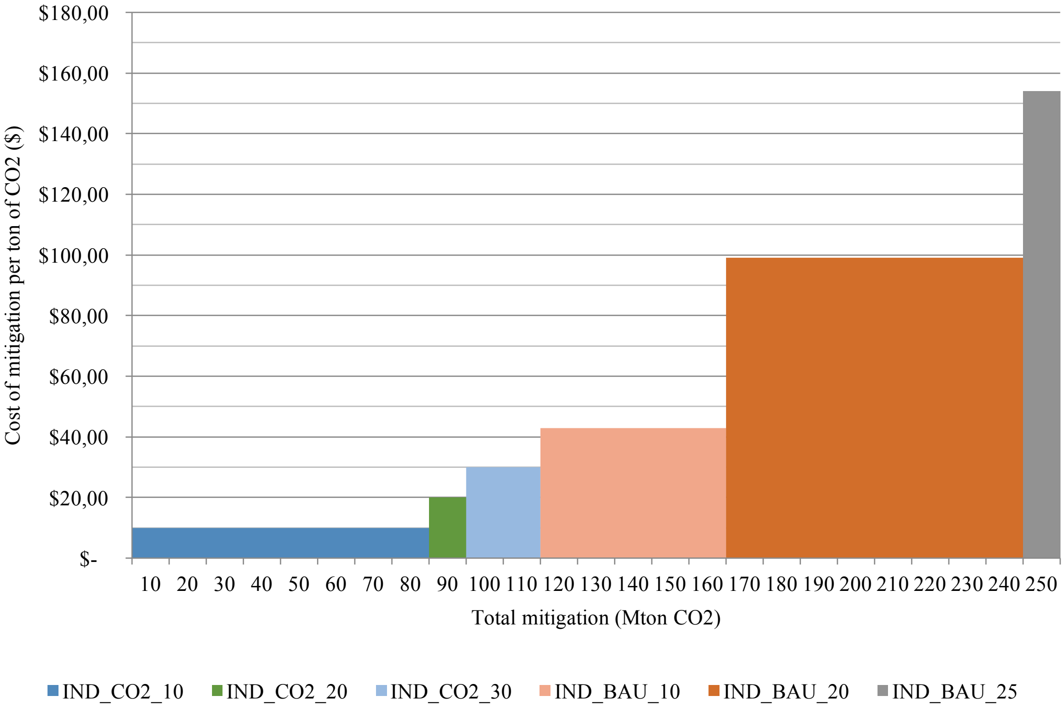

Figure C.14. MACC for industry sector under TIMES_TR.

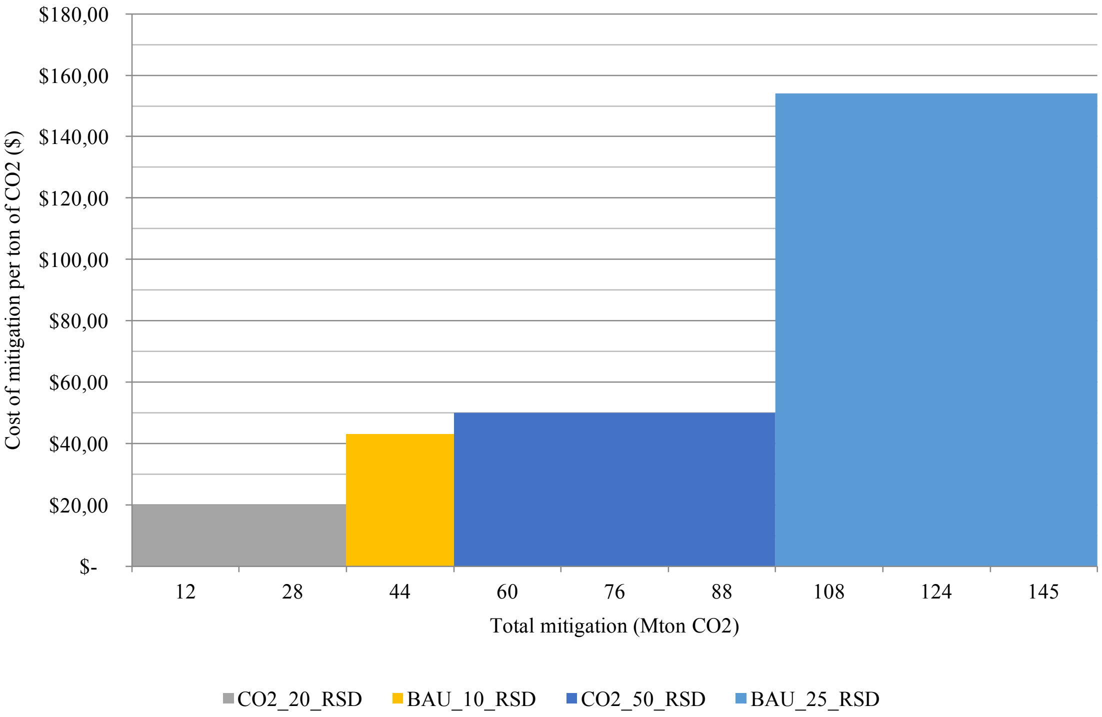

Figure C.15. MACC for RES and COM sector under TIMES_TR.

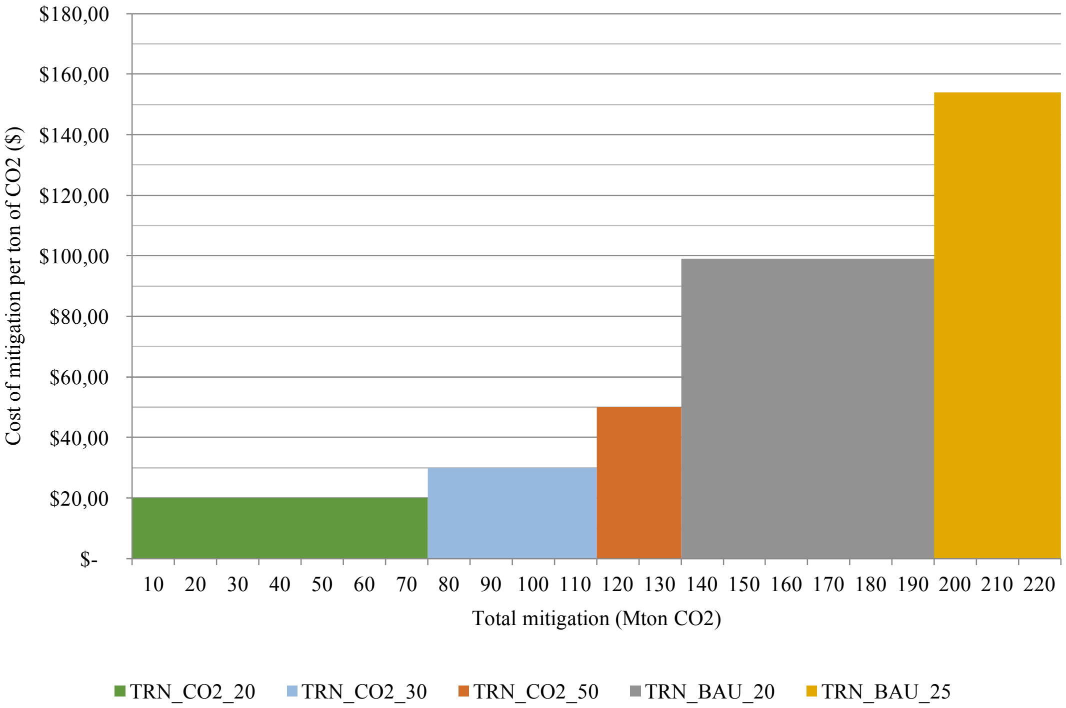

Figure C.16. MACC for transport sector under TIMES_TR.

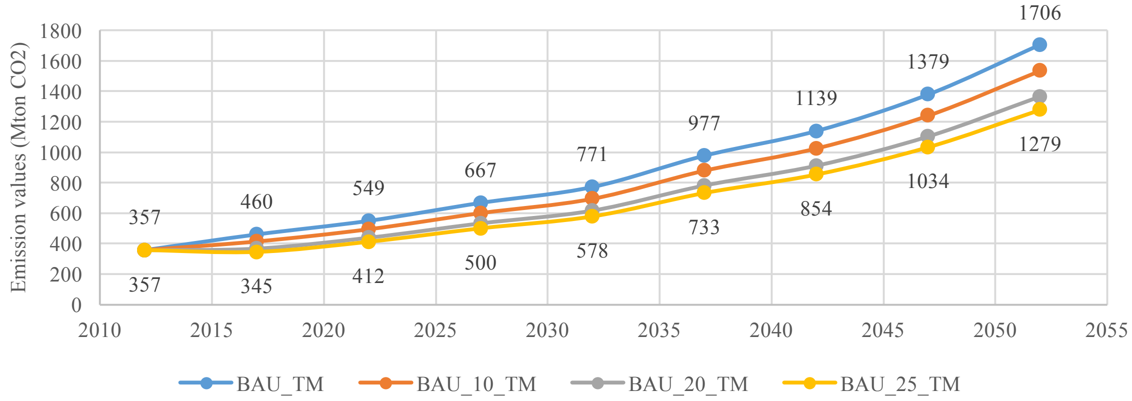

Figure C.17. Emission values under TIMES_TR emission bound scenarios.

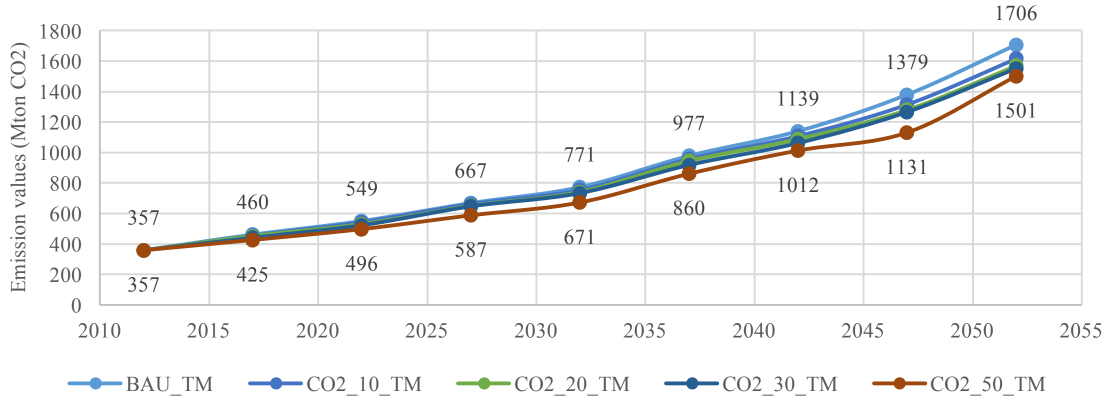

Figure C.18. Emission values under TIMES_TR emission tax scenarios.

Table C.1. Emission values under TIMES_TR emission bound scenarios.

	2012	2017	2022	2027	2032	2037	2042	2047	2052
BAU_TM	1221917	1953324	2243260	2729718	3057263	4240215	5289001	5880387	6498796
BAU_10_TM	1221917	1955300	2245620	2732585	3060579	4244415	5293898	5886315	6506131
BAU_20_TM	1221917	1959851	2251054	2739185	3068213	4254084	5305172	5899964	6523020
BAU_25_TM	1221917	1963390	2255280	2744318	3074151	4261605	5313941	5910580	6536156

Table C.2. Emission values under TIMES_TR emission tax scenarios.

	2012	2017	2022	2027	2032	2037	2042	2047	2052
BAU_TM	1221917	1953324	2243260	2729718	3057263	4240215	5289001	5880387	6498796
CO2_10_TM	1221917	1962306	2253983	2742710	3072397	4259357	5311404	5907767	6532789
CO2_20_TM	1221917	1962351	2254228	2742941	3072656	4259623	5311805	5908479	6533716
CO2_30_TM	1221917	1962703	2254460	2743066	3072912	4260435	5312608	5908927	6534287
CO2_50_TM	1221917	1963420	2255726	2745994	3075976	4263304	5315036	5915620	6536756